MASTER OF SCIENCE BY RESEARCH

The impact of catchment scale afforestation on water quality and ecology a case study in the Arrow catchment, Warwickshire

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Award date:
2021

Awarding institution:
Coventry University

The Impact of Catchment Scale Afforestation on Water Quality and Ecology: A Case Study in the Arrow Catchment, Warwickshire

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September 2020

A thesis submitted in partial fulfilment of the University's requirements for the Degree of Master of Research

Certificate of Ethical Approval

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Project Title:

The impact of catchment scale afforestation on stream water quality and ecology: a case study in the Arrow Catchment, Warwickshire.

This is to certify that the above named applicant has completed the Coventry University Ethical Approval process and their project has been confirmed and approved as Medium Risk

Date of approval:

06 March 2019

Project Reference Number:

P76456

The Impact of Catchment Scale Afforestation on Water Quality and Ecology: A Case Study in the Arrow Catchment, Warwickshire.

Abstract

With increasing pressure from the Water Framework Directive (WFD) (2000/60/EC) to improve water quality, the implementation of catchment management and natural measures is increasing. Natural Flood Management (NFM) is a widely accepted range of methods for natural mitigation of accelerated climate change, rapid urbanisation and water pollution by working with natural, hydrological and morphological processes, features and characteristics to manage the sources and pathways of flood water (SEPA, 2015; Lane, 2017). NFMs are relatively novel in their implementation and research regarding these techniques typically focus on flood function and capacity. Although research exists in relation to ecology and water quality, these topics are frequently a minor comment with little scientific evidence (e.g. Short et al., 2018), therefore, a scientific baseline was needed. The Arrow catchment, Warwickshire hosts a large NFM woodland creation scheme implemented by The Heart of England Forest (HoEF). To assess the Arrow catchment NFM a multi-criteria approach was implemented, consisting of a 6-month field investigation of ecological and physico-chemical indicators. It was found that the NFM improved habitat availability and provided opportunities for a range of floral and faunal species, as larger populations of fauna were present after implementation. The NFM was found to support a range of mammals, amphibians, birds, invertebrates and plants. Visual and recorded evidence of Great Crested Newt (GCN) (*Triturus cristatus*) and other amphibians in the NFM ponds were also found, along with mammal pathways across the NFM and macroinvertebrate populations of a moderate – high sensitivity to water pollution in NFM waterbodies. Furthermore, the NFM had no significant negative impact to the water quality of the catchment, as predominantly high-quality water was discharged from the NFM drainage channel into the river, suggesting the plantation was successful in retaining pollutants. Surface water quality also improved as water flowed through the main drainage channel of the NFM. However, the catchment remained impacted by nutrient eutrophication, most likely sourced from the nearby Water Treatment Works (WTW). Although the WTW did not exceed the legal maximum limits for pollutants, Total Reactive Phosphorus (TRP) concentrations failed the standards for good quality, Total Ammonia (TA) classified as 'Poor' in the river and Iron (Fe) concentrations exceeded boundary levels, remaining at a harmful level for aquatic life. A specific remediation scheme for the WTW is therefore needed in the Arrow catchment for the NFM to make any positive impact to the water quality of the River Arrow. The catchment also remained influenced by other factors such as heavy rainfall and seasonal variation, most likely from stormwater runoff from the agricultural land to the west of the River Arrow, as the NFM was located directly adjacent to the river in the east. This agricultural runoff is also a likely source of TA, as ammonia does not remain in form for great distances. It is therefore imperative that further research and monitoring of NFMs are conducted in the future to fully understand the capabilities of such installations.

Keywords: Natural Flood Management, Ecology, Physico-Chemical Water Quality, Water Framework Directive, Macroinvertebrates, Protected UK Species, Shannon Wiener, Diversity, GIS.

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Abbreviations

NFM	Natural Flood Management
HoEF	Heart of England Forest
SuDS	Sustainable Urban Drainage Systems
HSI	Habitat Suitability Index Assessment
GCN	Great Crested Newt
WFD-UKTAG	Water Framework Directive – UK Technical Advisory Group
WFD	Water Framework Directive
WHPT	Whalley, Hawkes, Paisley & Trigg
RICT	River Invertebrate Classification Tool
H’	Shannon Wiener’s Diversity Index
J’	Pielou’s Evenness Index
SEPA	Scottish Environment Protection Agency
CIRIA	Construction Industry Research and Information Association
WCA	Wildlife and Countryside Act (1981)
DO	Dissolved Oxygen
BOD_5	Biochemical Oxygen Demand (5 days)
TRP	Total Reactive Phosphorus
TN	Total Nitrate
TA	Total Ammonia
SP/PS	Specific Pollutants/Priority Substances
SS	Suspended Solids

Site Abbreviations

ST	Studley
WTW	Water Treatment Works
NFM DP	Natural Flood Management Discharge Point
CC	Coughton Court
FD	Ford
KC	Kings Coughton
ED	Eastern Extent of Main Drainage Channel
CD	Central Extent of Main Drainage Channel
WD	Western Extent of Main Drainage Channel
P1	Pond 1
P2	Pond 2

CHAPTER 1. INTRODUCTION

1.1. Context

Accelerated climate change, rapid urbanisation and water pollution are three major issues of the 21st Century. Urbanisation has increased within this century, with 60% of the world's population expected to live within urban areas by 2030 (Paul and Mayer, 2001). This continual change of natural land surface to vast areas of impervious surfacing is causing a detrimental disruption in the hydrological cycle (Charlesworth, Harker and Rickard, 2003). With an increase in the peak flow of stormwater and a decrease in lag time, urban rivers are flooding more frequently with contaminated urban stormwater, placing threat to large areas of floodplain infrastructure. This increase in contaminated urban stormwater discharged via conventional drainage has also become a primary driver of stream ecosystem degradation in urban catchments (Walsh *et al.,* 2005). Therefore, interest has shifted towards larger scale, sustainable and natural flood management strategies that aim to mitigate these issues at the catchment scale with significant multiple benefits (Dadson *et al.*, 2017; Nicholson *et al.,* 2019).

1.2. Natural Flood Management

Natural Flood Management (NFM) provides a catchment-based approach to reducing fluvial risk within urban areas and is considered as a sustainable approach to mitigating issues downstream by holding water in upstream, vegetated catchments, often also influenced by nearby urban catchments (SEPA, 2015). This approach is a subset of the established principal of Catchment-Based Flood management (CBFM), which refers to catchment scale management approaches that aim to modify the land use, land management, river channels and floodplains to reduce flooding (Dadson *et al.*, 2017). The key concept of NFM is the use of techniques that aim to work with natural and hydrological and morphological processes, features and characteristics in order to effectively manage the sources and pathways of flood water. NFM usually involves the slowing or retention of floodwater and covers a spectrum of techniques. Such techniques range from full-scale restoration activities (such as river or intertidal habitat restoration) to smaller scale land management techniques (such as upland drain blocking) (SEPA, 2015). NFM is also based on the established principle that flooding can be manipulated at the catchment scale instead of locally defending floodplains from inundation (Lane, 2017). A further principal of NFM is to balance and integrate the restoration of natural features and processes with existing land uses (SEPA, 2015).

NFM encapsulates a range of strategies to reduce flooding and mitigate the impacts of stormwater flooding and polluted runoff. These strategies are classified into three main categories: Woodland Creation, Land Management and River and Floodplain Restoration (SEPA, 2015). Table 1.1 outlines each strategy and the main action each strategy is designed for, as NFM is predominantly case based and the success level of each strategy is dependent upon various environmental conditions (Iacob *et al.,* 2014).

Table 1.1: NFM type and main action (SEPA, 2015).

Measure Group	Measure Type	Main Action
Woodland Creation	Catchment woodlands	Runoff reduction
	Floodplain woodlands	Runoff reduction / floodplain storage
	Riparian woodlands	Runoff reduction / floodplain storage
Land Management	Land and soil management practices	Runoff reduction
	Agricultural and upland drainage modifications	Runoff reduction
	Non-floodplain wetlands	Runoff reduction
	Overland sediment traps	Runoff reduction / sediment management
River and Floodplain Restoration	River bank restoration	Sediment management
	River morphology and floodplain restoration	Floodplain storage / sediment management
	Instream structures (e.g. large woody debris)	Floodplain storage
	Washlands and offline storage ponds	Floodplain storage

Of the NFM measures, this project investigates the strategy of woodland creation and establishment. As demonstrated in Table 1.1, the three types of woodland plantation outlined in the Scottish Environment Protection Agency NFM Manual (2015) comprise: Catchment Woodlands, Floodplain Woodlands and Riparian Woodlands. Woodlands planted in the wider catchment are planted in waterlogged soils prone to generating preferential flow pathways as streams. Floodplain woodlands are outlined as the most promising for flood management and can be planted on the floodplain in small blocks or as a large plantation. Riparian woodlands are planted in the buffer zone between the watercourse and the adjacent land. Although the research site is a catchment woodland, it is also situated on the floodplain and contains an existing riparian woodland (Refer to Section 3.7).

Although the main function of catchment woodlands is to reduce run-off, it is also believed that the approach may provide vital wildlife habitat and shelter for aquatic flora and fauna (SEPA, 2015). The Scottish Government Land Use Strategy (Scottish Government, 2016) and England Tree Strategy (Defra, 2020) has also identified a national priority for woodland expansion. A marked improvement of the catchments water chemistry is also often associated with such strategies (Iacob *et al.,* 2017). Furthermore, such afforestation schemes predominantly include plantations of Native Mixed Broadleaved species such as Oak (*Quercus* sp.) and Birch (*Betula* sp.), and Mixed Conifer species such as the native Scots Pine (*Pinus sylvestris*) and non-native Japanese Larch (*Larix kaempferi*).

CHAPTER 2. LITERATURE REVIEW

This chapter explores and analyses the relevant literature surrounding the issues, benefits, legislation, implementation and current methods of research in relation to NFM, with a particular focus on ecological benefits, water quality and analytical methodologies.

2.1. Context

Nature Based Solutions (NBS) such as NFM and Sustainable Urban Drainage Systems (SuDS) are becoming increasingly prominent within current research for a number of reasons. For example, the Pitt Review (2007) of the severe 2007 flooding across large areas of the UK and the introduction of updated legislative requirements responsive to the European Union Water Framework Directive (WFD) (2000/60/EC) and The Flood and Water Management Act (2010) prompted clarification of the responsibilities of authorities in flood prevention and mitigation and an improvement in flood management strategies with a new focus of sustainability. NFM solutions are also heavily influencing current policy decisions (Short *et al*., 2018). Policies regarding nature conservation (Eggermont *et al.,* 2015; International Union for Conservation of Nature (IUCN), 2016), urban regeneration (Marton-Lefèvre, 2012; Kabisch et al., 2016), climate change (Cohen-Shacham, 2016) and sustainable development (Maes and Jacobs, 2015) are all being reconsidered and updated to include NBS, NFM and SuDS measures. This is due to the multiple associated benefits of their implementation such as improved ecology, water quality, reduced flooding and social benefits, which have been reported in a number of studies (e.g. Wilkinson *et al*. 2014; Wolf, Duffy and Heal, 2015; Short *et al.,* 2018). NBS are also present within the European Commission's (EC) Horizon 2020 Societal Challenge 5 Climate Action, Environment, Resource Efficiency and Raw Materials' programme (EC, 2015) and is one of the IUCN's key programmes (IUCN, 2016). Due to this, it is predicted that NBS will be receiving significant attention in the near future (Short *et al*., 2018).

Several authors also place emphasis on the need for natural and sustainable solutions for flood management due to the serious ecological threats to rivers, streams and surrounding riparian vegetation from both point and diffuse sources of pollution (e.g. Paul and Mayer, 2001; Wenn, 2008; Rowińsky *et al.,* 2018). However, the success of each NFM strategy is dependent on environmental conditions. For afforestation, runoff reduction is likely to be larger from areas of grassland as opposed to shrubland. It has also been suggested that tree species composition and planting structure influence biodiversity gain (Iacob *et* al., 2014). Furthermore, small-scale schemes simply upscaled to catchment size are typically unable to mitigate flooding effectively (Iacob *et al*., 2017). As is the case with many new areas of research focus, some researchers regard NFM as a concept that lacks a clear definition (e.g. Short *et al*., 2018; Potschin *et al.,* 2016), despite the publication of both an NFM and SuDS handbook in 2015 (SEPA, 2015; Woods Ballard *et al.,* 2015). This project will therefore strive to provide some clarity in relation to the unclear secondary benefits of the water quality performance of a catchment scale NFM scheme and the opportunities created for terrestrial and aquatic ecology.

2.2. Key Issues and Articles

Table 2.1 outlines the key topics and threats surrounding NFM, water quality, ecology and biodiversity and the fundamental studies to be included within this section.

Table 2.1: Key topics and threats surrounding NFM and respective key studies.

Key Topic	Description	Key Studies
Studies focusing on flood capability of NFM measures	• Dominantly GIS and flood modelling based • Focus on accuracy and calibration • Case by case consideration • More research needed	• Iacob *et al.* (2017) • Sonnenborg *et al.* (2017) • Aspinall and Pearson (2000)
Ecological benefits of NFM measures	Opportunities for terrestrial and aquatic flora and fauna: • Shelter • Foraging • Breeding • Larger communities • Improved water quality for aquatic biota • More research needed	Handbooks • SEPA (2015) • Woods Ballard *et al.* (2015) Studies • Iacob *et al.* (2014) • Rowińsky *et al.* (2018) • Short *et al.* (2018) • Archer and Newson (2002)
Key Threat – is NFM the answer?	**Causes**	**Key Studies**
Water quality degradation	Point sources include: • Waste Water Treatment Works • Victorian sewers • Industry • Domestic Diffuse sources include: • Agricultural runoff • Contaminated urban runoff • Urban storm water Physico-Chemical indicators and bioindicators required	Pollution sources: • EA (2007) • Wenn (2008) Physico-Chemical indicators: • Li and Zhang (2010) • Zhao and Marriott (2013) • Wheater and Evans (2009) • Wilkinson *et al.* (2014) • Iacob *et al.* (2014)
Habitat degradation – Species presence	• Urbanisation • Water quality degradation • Plastic waste • Pollutants • Physical changes	Bioindicators: • Le Viol *et al.* (2009) • Wenn (2008) • Shannon and Weaver (1949)

2.3. Updated Legislation

2.3.1. Flooding and Water Quality

The European Water Framework Directive (WFD) (as amended) transposed into UK law in 2003, places emphasis on the improvement and protection of inland surface waters, estuaries, coastal waters and groundwater. The UK framework for delivering the WFD is through River Basin Management Planning for each River Basin District (RBD) (Figure 2.1) and associated Water Bodies. In England, current Ecological Status is classified in all Water Bodies by the Environment Agency (EA). Waterbodies are classified via the assessment of ecological and physico-chemical indicators (EA, 2010) in accordance with WFD UK Technical Advisory Group (WFD-UKTAG) standards. In response to the WFD, the EA, Scottish Environment Protection Agency (SEPA) and Natural Resource Wales (NRW) have placed improvement targets for each RBD and catchment within their boundaries, with the intention of reaching 'Good' ecological, chemical and geomorphological status in all rivers by 2027. Furthermore, the EU Wastewater Treatment Directive also requires major treatment works to introduce tertiary treatment to reduce nutrient loads (Wheater and Evans, 2009).

Figure 2.1: River Basin Districts (RBD) map (EA, 2015).

Similarly, the Flood and Water Management Act (2010) has placed a requirement for all flood and coastal management authorities in England and Wales to produce strategies for the better management of fluvial and coastal flood risk. This act encourages local councils to work cohesively with the EA/NRW to meet the requirement of the design and implementation of efficient and sustainable surface drainage management strategies. Authorities are also encouraged to consider current environmental targets (The Flood and Water Management Act, 2010). Moreover, legislation such as the National Planning Policy Framework (NPPF, 2018) and Town and Country Planning (EIA Regulations) (2017) have emphasised the priority use of sustainable and natural drainage measures in major developments since 2015, with recent updates placing more pressure to comply (Ellis and Lundy, 2016; NPPF, 2018). The requirement for the installation of sustainable surface water management approaches for all developments are now also included within the majority of local district strategies.

2.3.2. Protected Species

A number of UK native species are protected by The Wildlife and Countryside Act (1981) (UK) and The Habitats Directive (2000), formally known as The European Communities Council Directive on the Conservation of Natural Habitats and Wild Fauna and Flora. Concern for UK native species and biodiversity has been rapidly rising due to the impacts of urbanisation and have recently become one of the key motivations for the installation of NFM (SEPA, 2015). Biodiversity has also been included in the four pillars of Sustainable Drainage (SuDS) in CIRIAs updated SuDS manual (Woods Ballard *et al.*, 2015). Various methods for the analysis of protected species exist, however, these are typically used by professional agencies and are rarely used in research. These methods include techniques such as spatial analysis of species records collected by local biological record centres and specialised species surveys and habitat suitability assessments for species such as bats and Great Crested Newt (GCN) *(Triturus cristatus)*.

2.4. The Function of Natural Flood Management

In the last 10 years, an increased interest in research into the function and capacity of NFM has become increasingly apparent. However, within NFM research, greater emphasis is often given to investigating the performance of models and decision support platforms in relation to the functionality of NFM drainage measures (e.g. Viavattene *et al.,* 2008; Ellis *et al*., 2012). Although these studies are useful in terms of functionality, chemical water quality potential and capacity prediction, they pay minimal consideration to potential opportunities for flora and fauna.

The use of GIS and modelling has also become the focal point for many studies of NFM and catchment management (e.g. Aspinall and Pearson, 2000; Viavattene *et al.*, 2008; Iacob *et al*., 2017; Whitehead *et al*., 2018; Li *et al.,* 2018). However, these researchers place a higher level of concern upon investigating the functionality of NFM, with a dominant focus on flood modelling, GIS and flow capacity. For example, a recent study by Iacob *et al*. (2017) applied the distributed WaSiM-ETH hydrological model, which quantifies and assesses land use and water infiltration for individual cells, to a mesoscale catchment. A significant increase in peak flows from climate change was modelled and it was found that afforestation had the ability to reduce some of the increased flow, with the greatest benefit provided by coniferous afforestation. The results of this study are clear and concise but are currently based only on prediction. The results are also somewhat contradicted by Sonnenborg *et al*. (2017), which criticise the WaSiM-ETH model and utlise the SVAT implementation in SHE SWET (the MIKE SHE SWET model), which provides an energy-based description of evaporation from vegetation. In this case, greater groundwater recharge with broadleaved woodland was predicted on sandy soils, however, this was terrain dependent.

These researchers provide a detailed explanation of how they validated and calibrated their model, which is a vital aspect of Geographical Information Systems (GIS) and hydrological modelling. The results of such papers are therefore likely to be accurate and valid as predictive error is reduced and provide a key data source for this research field. However, the majority of studies published in recent years place significant focus on the function of NFMs as a method for flood water reduction and appear to be somewhat narrow, omit ecology or make unsupported blanket conclusions in relation to ecological benefits (e.g. Mak, Scholz and James, 2017; Lane, 2017; Dadson *et al.,* 2017; Wilklinson *et al*., 2019; Nicholson *et al.,* 2019).

Furthermore, some earlier research into the use of GIS to assess ecology was carried out by Aspinall and Pearson (2000). This study outlined a multi-criteria approach including eco-hydrological modelling, remote sensing, landscape ecological analyses and GIS to develop a series of indicators to monitor water quality, landscape variability and ecological function. This demonstrates that this older method and type of study can also be a useful and reliable tool to monitor river catchments and ensure the implementation of the most effective NFM scheme for both function and ecological opportunities.

GIS has proven to be a valuable analytical tool and would benefit a number of studies that ultimately fail to provide spatial and temporal evidence to validate their assertions (e.g. Le Viol *et al.,* 2009; Graham *et al.,* 2012; Briers, 2014; Jose, Wade and Jefferies, 2015). For example, analysis of species distribution, faunal observations, macroinvertebrate communities and habitats could be analysed in a spatial and temporal context and the ecological performance (the capability to influence ecology with the provision of opportunities) of NFM measures could be assessed. As NFM research has only become prominent as the impacts of land use change and climate change accelerate, a focus on the challenges and limitations of current research and the pressing requirement for further research is apparent. This is emphasised within Li *et al.*'s (2018) study of automatic near real-time flood detection, in which the promising performance and high feasibility of the use of Suomi-NPP/VIIRS (Suomi National Polar-orbiting Partnership/Visible Infrared Imaging Radiometer Suite) data to build the VNG Flood V1.0 was demonstrated and the researchers stressed the need for the continuation of such research. This research is paramount as this would enable the strategic planning and placement of NFM measures within pollution pathways to protect aquatic communities.

2.5. The Ecological Benefits and Impacts of Natural Flood Management

Although some studies criticise NFM strategies for causing negative impacts to ecology such as damage to water quality (e.g. Iacob *et al.,* 2014), it is widely accepted that NFM provides some benefit to ecology and the local ecosystem (e.g. Cook et al., 2016; Wingfield *et al.,* 2019). Although NFM studies typically focus on function (as outlined in Section 2.4), ecological research is gradually becoming more pronounced and is often referred to within governmental publications. For example, a report published by the EA (Barlow, Moore and Burgess-Gamble, 2014) highlights the necessity for research regarding the ecological impact of NFM projects for habitat, species and ecological quality.

In addition, in 2015, around the same time as the release of CIRIA's 2015 SuDS manual update, SEPA released an NFM manual (SEPA, 2015). Within this manual, SEPA emphasise NFM as widely recognised strategy to mitigate flooding, whilst also providing multiple benefits. It is claimed that the techniques can incorporate and contribute to improvements in biodiversity, water quality, and carbon storage. SEPA also state that many NFM measures seek to restore or strengthen an ecosystem, which in turn supports numerous habitats and species and the most effective measure for ecology is the construction of a wetland system due to high productivity and connectivity. Other measures such as river restoration are also claimed to be beneficial for in-stream riparian vegetation. Furthermore, in relation to forest plantations, it is stated that such measures provide important wildlife habitat and the increased canopy shade can provide shelter for water-based flora and fauna (SEPA, 2015). Although no physical data is provided in the manual, this assertion is supported by the findings of several researchers (e.g. Iacob *et al.*, 2014, Rowińsky *et al.*, 2018; Short *et al.*, 2018). For example, a study by Rowińsky *et al.* (2018) provides an interesting exploration of the ecological possibilities and implications of the implementation of aquatic and riparian vegetation. The researchers state that, besides directly supporting biota, aquatic and riparian vegetation can process nutrients and harmful substances, therefore emphasising the need for the implementation of such systems. An increase in riparian habitat and ecosystem services were also reported by other authors (e.g. Wilkinson *et al*., 2019).

Furthermore, Iacob *et al.* (2014) evaluated the benefits of NFMs based on 25 previous studies across the UK, Europe and New Zealand. This review concluded that afforestation schemes succeeded in reducing surface runoff and suggest that the complex root structures of replanted woodland could significantly augment biodiversity and soil and water quality due to a diversion of runoff and a reduction in sediment mobilisation. This conclusion is supported by other studies within the wider literature (e.g. Dadson *et al.,* 2017; Short *et al.*, 2018), although in many studies this benefit is only briefly mentioned (e.g. Wilkinson *et al*., 2019). However, despite an improvement to ecology being a significant motivation of NFM, this was refuted in a further study by Iacob *et al.* (2017) suggesting trees, particularly conifers, significantly increase the risk of the transfer of pollutants from the air to the soil and surface waters due to the dense nature of a conifer canopy. The researchers suggest that if this measure is poorly managed, it can cause negative impacts to water ecology. However, due to the model-based nature of this study, no actual scientific data is provided to support this point. Despite this, these findings leave a degree of uncertainty in relation to the performance of NFMs and the ability for pollutant filtration.

Furthermore, in Archer and Newson's (2002) study of hydrological and instream habitat impacts of upland afforestation and drainage, a link between flow regime and water quality/sediment loading is concluded, suggesting these parameters are likely to be defining elements of the overall instream habitat quality of headwater catchments. The researchers claim that the methodology produced in the paper provides a comprehensive, continuous and quantitative picture of changes in hydrological regime caused by upland afforestation and is therefore relevant to current assessments of instream physical habitat. The researchers also suggest that low invertebrate numbers and low levels of fish recruitment may be attributable to changes in flow regime caused by upland afforestation. Although several studies exploring the ecology of small afforestation schemes exist, further research in relation to NFM measures at the catchment scale is needed as the potential ecological benefits at this scale is rarely investigated.

Furthermore, in depth ecological research of urban SuDS also appears to slightly more established within the literature in comparison to catchment scale NFM. This is perhaps due to the smaller size, high demand and lower cost for SuDS. However, SuDS research is still relevant in relation to NFM, as the findings can be treated as a baseline for NFM research. A key example of urban SuDS is a study by Le Viol *et al.* (2009), in which the researchers investigated macroinvertebrates within highway retention ponds and found that these retention ponds acted as a biodiversity refuge from the human dominated landscape. A notion that ponds support higher numbers of rare taxa than other freshwater habitats such as rivers also exists within the wider academic literature (e.g. Williams *et al.,* 2003; Biggs et *al.,* 2005 and Lukacs *et al.,* 2013). This is an interesting hypothesis that is also investigated within this project, as the Heart of England Forest (HoEF) afforestation site contains two man-made ponds (refer to Section 3.7). In terms of the water quality of SuDS, it is was found that the most diverse habitats are those that have colonised within permanent shallow water SuDS, as these ecosystems are the least vulnerable to pollutants (HR Wallingford, 2003). This was supported by Heal (2000) as large communities were found within shallow SuDS, with no evidence of pollution. An improvement of water quality and habitat size has also been noted in other various studies (e.g. O'Donnell *et al*., 2018).

Furthermore, CIRIAs SuDS manual also outlines that standing water bodies such as detention basins, ponds, wetlands and soakaways may prove to be the most beneficial and encouraging for wildlife (Woods Ballard, 2015). The manual also states that SuDS can offer green corridors, breeding opportunities, shelter, food and foraging habitat for various faunal species and may also contribute towards national targets. This is supported by studies within the wider academic literature (e.g. Four Countries Biodiversity Group, 2012; Graham *et al.,* 2012; Jose, Wade and Jefferies, 2015). It is likely that similar NFM strategies such as woodland planting will also have such benefits, as woodlands are one of the UK's most diverse habitats, providing shelter for rare and native flora and fauna. Finally, a common conclusion in relation to obtaining maximum benefits from the implementation of NFM is that each type of woodland creation, land management and river/floodplain restoration should be considered individually. The best strategy for each case is entirely dependent on landscape setting and catchment characteristics (e.g. Iacob *et al.*, 2014; Lane, 2017), as the environmental condition of a water catchment is often linked with external geographic factors (Aspinall and Pearson, 2000).

2.6. The UK National Ecosystem Assessment

The use of the UK National Ecosystem Assessment (NEA) is commonplace when evaluating ecosystems and is used in several papers within the subject area (e.g. Eggermont *et al.*, 2015; Mak, 2015; Mak, Scholz and James, 2017; Short *et al.*, 2018). The UK NEA recognises that humans are an integral part of the ecosystem and activities carried out are subject to the natural limits and function of the ecosystem (Maltby, 2010; Mak, 2015; Mak, Scholz and James, 2017). Another method used within this subject area is the Millennium Ecosystem Assessment. This technique divides Ecosystem Services into four categories: Supporting, Provisioning, Regulating and Cultural (MA, 2005; Wade, Jose and Lundy, 2012; Tzoulas and James, 2009). The need to assess urban ecology and greenspace with a multi-disciplinary approach is also highlighted by James *et al.* (2009).

Although this method has proven to produce valid and often useful results such as those of Iacob *et al*. (2014), the studies that utilise these methods typically only outline the creation of an ecosystem but proceed to solely focus on Ecosystem Services (direct or indirect human benefits of ecosystems) (UKNEA, 2011) and neglect to determine the ecological benefits for floral and faunal species (e.g. Wolf, Duffy and Heal, 2015). For example, this method can be seen in recent publications by Rowińsky *et al.* (2018) and Iacob *et al*. (2014), in which the researchers continuously focus on ecosystem services for anthropogenic benefit, rather than the actual potential for non-human biota.

2.7. Ecological Cost-Benefit Analysis

A common theme amongst NFM and sustainable drainage research is cost-benefit analysis due to the higher cost and complexity of implementation (e.g. Waylen *et al*., 2017; Short *et al*., 2018). In a recent cost-benefit study of an afforestation scheme in Scotland (Dittrich *et* al., 2018) it was concluded that NFMs, particularly afforestation on hillslopes and floodplains, are being increasingly considered as cost-effective strategies for both flood reduction and ecosystem services. 'Net Present Values' (NPV) were identified for all afforestation types with the dominant benefits related to ecosystem services.

Many researchers agree that ecology benefits are one of the major incentives for NFM (e.g. Wilkinson *et al.,* 2014; Short *et al*., 2018), however, some studies (e.g. Wolf, Duffy and Heal, 2014; Iacob *et al.*, 2014) concluded that although these measures were a net asset, ecological implications were mixed and uncertain. Although this project aims to provide baseline information in relation to these benefits, which will aid cost-benefit analysis research, it does not directly address this topic.

2.8. Indicators for Ecological Assessment

Water quality is widely used as an ecological quality proxy due to the relative accuracy, importance and well-established links between the two parameters. For many years, the water quality and ecological health of rivers have been monitored and researched with the use of both biological and chemical indicators (Wenn, 2008). However, much like ecology, scientific investigations of the specific water quality of implemented NFM strategies is notably absent or rare within the literature, therefore leaving a sizeable research gap. Additionally, research focused on assessing or enterprising methods for the improvement of water quality are rare in the wider literature (e.g. Iacob *et* al., 2014) or are briefly mentioned within papers focused more primarily on quantity, with little/no scientific evidence (e.g. Short *et* al., 2018; Wingfield *et al.,* 2019). Presently, water quality analysis remains a focus for official governmental bodies such as the EA, DEFRA and SEPA and a small number of researchers (e.g. Barber & Quinn, 2012). However, it is has become increasingly apparent that the SuDS branch of NFM strategies in particular is more researched in terms of ecological and water quality (e.g. Charlesworth *et* al., 2012; O'Donnell *et al.*, 2018), which is likely due to the long-established inclusion of SuDS within urban developments and industry (Woods-Ballard *et al.*, 2015).

The remainder of this section will investigate and evaluate the most relevant studies, methods and parameters of water quality and aquatic ecology investigation in rivers, streams and ponds to inform the methodology of this project.

2.9. Bioindicators

2.9.1. Macroinvertebrate Analysis

The study of macroinvertebrate communities as a bioindicator for ecology and water quality is a common and widely accepted methodology seen throughout relevant academic literature and are used as an official bioindicator by the four UK environmental agencies (Clarke and Davy-Bowker, 2014). These agencies implemented the official River Invertebrate Classification Tool (RICT) (FBA, 2020a), which uses the River Invertebrate Prediction and Classification System (RIVPACS). This statistical model uses the EU WFD biotic index Whalley, Hawkes, Paisley & Trigg (WHPT) (WFD-UKTAG, 2014) scores from observed invertebrate fauna in coalition with 1978-2002 RIVPACS datasets to determine macroinvertebrate populations in pristine conditions and predicts species abundance and taxa that should be present based on the habitat (Clarke and Davy-Bowker 2014; FBA, 2020b). This is a successful tool which uses standardised procedures to ensure complete accuracy. For validity, macroinvertebrates are collected with the standard 3-minute sweep/kick sample which involves 3-minute agitation of bottom sediments and sweeps in littoral zones and differing biota to ensure the collection of benthic and nektonic macroinvertebrates (Le Viol *et al.*, 2009; Briers, 2014; Bradley *et al*., 2017).

Although macroinvertebrates are rarely used in the context of NFM analysis within the literature, a key example of their use as a bioindicator is a study by Wenn (2008) in which macroinvertebrate response to a remediation scheme of two Waste-Water Treatment Works (WWTW) in West Yorkshire was assessed.

The study evaluated correlations between ecological and physico-chemical indicators (BOD and Ammonia) over the course of 2006 and concluded that the sensitivity of macroinvertebrate communities highlighted pollution events that frequent chemical testing may overlook. This paper also highlights the main issue of the lack of studies that evaluate any type of long-term remediation. This is a strong study, as several other biological and chemical indicators such as BMWP (Biological Monitoring Working Party,1978), Shannon Wiener (Shannon and Weaver, 1949), BOD and Ammonia are used to support the eventual conclusions of the remediation schemes insufficiency to improve ecology.

A further example of macroinvertebrates and sustainable flood management is Le Viol *et al's* (2009) study of the ecological potential of highway stormwater retention ponds. Via the analysis of macro-invertebrate communities, the researchers demonstrated clear links between high quality water and high ecological status by using macro-invertebrates as the sole indicator. However, this methodology is often criticised, as macroinvertebrates are impacted by external environmental conditions and are therefore commonly used within a multi-framework analysis (e.g. Heal, 2000; James *et al.,* 2009; Shore *et* al., 2016*,* Bradley *et al.*, 2017). Furthermore, the frequency and methodology of macroinvertebrate sampling varies greatly within current research, with snapshot studies the most common. However, the life cycle of macroinvertebrates is varied as different species thrive in differing seasons and communities alter in a matter of weeks. However, this issue is reduced by the use of a continual sampling technique across the four seasons and detailed identification, as seen in studies such as Bradley *et al*'s (2017) investigation of groundwater abstraction and sediment loading and Wenn's (2008) study of the WWTW remediation.

2.9.2. Botanical Assessment

The Shannon Wiener Index of Diversity (H') is a well-established and effective equation for of the analysis of both floral and faunal diversity and has been used as the standard methodology in ecological and biological studies since its development by Shannon and Weaver (1949) (e.g. MacArthur, 1955; Patten, 1959). Although primarily used in a biological context, the index has also been frequently seen within studies of ecological diversity (e.g. Barbour *et al.,* 1999; Krebs, 2009; Magurran, 2003; Li *et al*., 2019). No evidence of the index's use in the context of NFM is apparent in the wider literature, however, a key example of its use as a bioindicator is Wenn's (2008) study, in which the index is used to assess macroinvertebrate community response to the implementation of a WTW pollution remediation scheme. However, despite its usefulness in determining the diversity of macroinvertebrate colonies, it is often discarded in favour of stronger BMWP/WHPT methods (e.g. Le Viol *et al.*, 2009; Bradley *et al.,* 2017).

Additionally, despite the index's use for over sixty years, its effectiveness and interpretation is still debated by researchers. For example, Goodman (1975) and Strong (2016) heavily criticize the index, suggesting the results provide no meaning and that H' is either an imperfect index of diversity or a biased measure of evenness. However, the contrary is debated by other researchers such as Jost (2006) and Spellerberg and Fedor (2003) who praise the index for its usefulness and plea for its continued preferential use. Therefore, it is apparent that further research a useful and simple index to effectively and reliably assess biodiversity of measures such as NFM would be beneficial.

2.10. Physico-Chemical Indicators

2.10.1. Acid Conditions

pH was used as an indicator many years prior to the WFD and is a standard indicator for acidification. Anthropogenic acidification from burning of fossil fuels has potentially detrimental consequences for aquatic communities, as oxidation of sulphur dioxide and oxides of nitrogen emissions form sulphuric acid and nitric acid, which are subsequently deposited by precipitation. Acidification occurs in areas with thin soil and a low buffering capacity (small quantities of K, Mn and Ca in the soil) (WFD-UKTAG, 2014).

2.10.2. Temperature

Water temperature is a key indicator for water quality and is a parameter in the WFD as it can directly affect the survival of aquatic species and indirectly shift water chemistry. Due to climate change, a change in annual averages is likely to heavily impact/degrade aquatic communities and is therefore a major cause for concern (WFD-UKTAG, 2008b).

2.10.3. Biochemical Oxygen Demand and Dissolved Oxygen

Although Biochemical Oxygen Demand (BOD_5) and dissolved oxygen (DO) are amongst the oldest and most established UK parameters for the assessment of organic pollution in rivers (Jouanneau *et al.*, 2014), their use in the context of NFM installations is limited. BOD_5 and DO are effective pollution indicators and determine the amount of oxygen taken up through the respiratory activity of microorganisms growing on organic compounds in river samples in the field (DO) and after incubation at 20 °C for 5 days (BOD), indicating the remaining O_2 available for aquatic life. The traditional 5-day incubation method is used to assess BOD_5 as this is the longest estimated time for water travel from source to estuary in the UK (Jouanneau *et al.*, 2014). High BOD_5 values indicate a high rate of microbial oxidation of waste matter, resulting in a high level of O_2 use. In previous years, researchers have identified high BOD_5 values in urban rivers (e.g. Mitchell, 2005) caused by the increased influx of urban storm water pollutants. However, other researchers believe NFM strategies such as woodland planting have the capacity to intercept pollutants such as phosphate within the root structures (e.g. Iacob *et al.,* 2014) and may therefore be able to improve oxygen levels and water quality by reducing BOD and eutrophication. This was also found by Scholz (2004), in which it was concluded that sustainable drainage measures provide a generally good water quality but BOD and pollutant values varied across seasons and should therefore be studied across the hydrological year (12-month period from 1st October to 30th September the following year (USGS, 2016).

2.10.4. Nutrient Pollution

As with heavy metals, the investigation and analysis of nutrients (e.g. phosphate, nitrate and ammonia) within NFM strategies is somewhat rare. Nutrients are frequently monitored and used to assess the potential for eutrophication and ecological quality in rivers, lakes, estuaries and coastal waters. High levels of phosphate, nitrate and other nutrient contaminants are causing a high level of concern within the current literature, as it likely that a large number of UK rivers are not achieving 'Good' ecological status within the WFD framework due to elevated levels of nutrients, primarily phosphate. Furthermore, it is also believed that such elevated levels are caused by storm water runoff from cities and farms and may possibly take decades to recover (EA, 2007). Since the EA publication, nutrient loading has remained a high concern, with the phosphate and ammonia standards lowered by the UKTAG for the 2015-2021 second cycle (UKTAG, 2013;2014). This concern is confirmed by the findings of Shore *et al.'s* (2017) study of phosphorus pressures on stream ecology in agricultural catchments. The researchers analysed both baseflow and stormflow conditions at the catchment scale and claim that total reactive phosphorus was consistently low during baseflow conditions, where elevated levels of total reactive phosphate frequently exceeded the environmental quality standard (EQS) of 0.035 mg/l^{-1} during storm water conditions. This was also identified within the same catchments in previous years (e.g. Jordan *et al.,* 2012; Melland *et al.,* 2012). This highlights the need for an effective storm water control methodology such as NFM, as elevated levels of nutrients are causing irreparable damage to the UK's ecology via extensive eutrophication (Mallin and Cahoon, 2020).

This point is also highlighted in a study by Wilkinson *et al*. (2014). The researchers use secondary data from the Environment Agency (2010) to assess the potential for an improvement to water quality with a catchment scale engineering approach. The study includes the analysis of ammonia, phosphate, nitrate and dissolved oxygen within the catchment over the period of 2006-2009. The researchers conclude that catchment management approaches may be successful at reducing pollution, but require the cooperation of multiple stakeholders and residents, as management at the field- and farm-scale remains crucial to water quality outcomes. However, with the implementation of such large-scale schemes, it is noted that it is likely to take several years to detect any change in the sediment and nutrient regime at the catchment scale (Haygarth, 2010; Wilkinson *et al.,* 2014). Although this study is useful and outlines the potential for pollution reduction, it highlights the need for more in-depth research of these strategies.

2.10.5. Specific Pollutants (SP), Priority Substances (PS) and Suspended Solids (SS)

A large number of Specific Pollutants and Priority Substances are heavy metals as, in high concentrations, these are highly toxic to aquatic life. Testing of heavy metals in solution, suspended and bed sediments is a common chemical indicator to determine water quality, as this method is also used by the EA and is seen within relevant academic literature. However, specific scientific investigations of pollutants within NFM or catchment afforestation is notably absent from current literature. Despite the research gap for NFM systems, several studies have investigated this topic within river systems in relation to ecology and water quality. For example, a study by Zhao and Marriott (2013) focuses on heavy metals in the Severn catchment (of which the Arrow catchment is a tributary). The concentrations of five significant heavy metals (Pb, Zn, Cu, Co and Cd) were determined within soil samples from depths of every 10 cm using an Atomic Absorption Spectrometer (AAS). Analysis of these five metals appears to be common within both UK and international studies (e.g. Dawson and Macklin, 1998; Su *et al.*, 2017) perhaps due to common presence and toxicity to aquatic biota. Significant concentrations of Pb and Zn were noted within the Avon catchment which was attributed to Cambrian metal mines upstream.

An alternative method suggested by Li and Zhang (2010), comprised the analysis of several contaminants in the Han River, China and discerned the most threatening according to season. Contaminants were analysed with the inductively coupled plasma-atomic emission spectrometry (ICP-AES) method. This is near identical to the ICP-OES (inductively coupled plasma-optic emission spectrometry) method also used in Scholz's (2004) study of water quality management of stormwater ponds. (Both the AAS method and ICP-AES/ICP-OES method are common and widely accepted within this field. Both methods are notably reliable, accurate and have differing strengths and weaknesses. For example, the ICP-AES/ICP-OES methods are more expensive but can detect more elements at a faster pace than AAS. The papers that use either of these methods is considered strong, accurate and supported by reliable data.

However, although these studies are useful and accurate, many only consider river sediment and do not include analysis of suspended solids in river water, which can provide useful data in relation to the transportation of pollutants within suspended sediment and soluble pollutants (e.g. Scholz (2014) and Li and Zhang (2010)). Furthermore, in many studies, the number of samples taken from each site can vary significantly (e.g. Li and Zhang (2010); Zhao and Marriott (2013)). This can result in a negative impact to the statistical analysis and results, therefore decreasing the validity of the conclusions of such papers.

2.11. Summary

In summary, as a recent approach to flood management, sustainable NFM approaches are deemed to be of higher ecological value than those using hard engineering approaches, as hard engineering schemes are often considered to cause significant environmental impacts due to a disruption of natural flow and storage processes (Iacob *et al.*, 2014). However, specific evidence is still sparse and evidence-based research is required to assess its effectiveness. Furthermore, existing research into the topic of NFM is typically focused on functionality and water quality potential with little or no focus on the potential impact on ecological quality, which is likely a consequence of the current flood reduction and modelling focus (e.g. Iacob *et al.*, 2014; Lane, 2017). Similarly, the lack of research in an ecological context is often raised when discussing the wider topic of Sustainable Drainage Systems (e.g. Heal, 2000; Charlesworth, Harker and Rickard, 2003). Therefore, further research into the impact of NFM design for both aquatic and terrestrial wildlife is greatly needed to provide evidence to maximise the benefits for instream water and ecological quality. Furthermore, it has been suggested that the impacts of NFM strategies are often site-specific and require further research and planning to ensure the most beneficial and suitable schemes are implemented into catchments (Iacob *et al.*, 2014). Furthermore, the need for focused research regarding NFM implementation is also highlighted within a report published by the Environment

Agency (2014). The necessity for research regarding the ecological impact of NFM projects for habitat, species and ecological quality is also outlined.

This project therefore investigates the notable gap in current academic research by using monitored data to understand the influence of NFM across a catchment impacted by both urban and rural influences and includes tree plantations at different stages of maturation. This multi framework research approach will allow an understanding of their impact on outflow water and ecological quality. Furthermore, an assessment of spring and summer/autumn would also demonstrate performance in differing seasons and provide evidence to encourage the implementation of the most beneficial schemes.

Finally, conclusions such as successful pollutant filtration and habitat creation drawn from the majority of the NFM papers reviewed (such as Rowinsky *et al.,* 2018 and Iacob *et al*., 2017) are positive, encouraging and promote the adoption of appropriate NFM measures such as catchment woodlands. However, relevant research also highlights the necessity for the installation of the appropriate NFM scheme for the landscape characteristics of the catchment to ensure the maximum benefit. Therefore, new research into these systems is needed and may also inspire further research of the topic to ensure NFMs continue to develop into a key method to tackle urban stormwater runoff and climate change.

CHAPTER 3. METHODOLOGY

3.1. Introduction

This chapter will outline the methodology of the project, which adopts a multi-criteria approach of qualitative and quantitative data over a 6-month period to construct an accurate assessment of the ecological status of the Arrow catchment over time and determine any possible impact from the NFM to achieve the project aim. The methodology was designed to address the strengths and weaknesses of existing research and set a baseline for future research. The sections below will provide a detailed overview and rationale of the research design, process, case study location and analytical methods used for this study. All aspects of the methodology were subject to ethical approval (refer to Appendix A).

3.2. Purpose / Research Justification

To ensure the methodology of this project was relevant, ethical and up to date, the approaches of several studies within the current literature were analysed in Chapter 2 (Objective 1). The approaches most suited for this project were selected and incorporated into the research method to effectively and ethically analyse the research question. The broad elements of the multi-criteria research design of this project and justification for selection are outlined in Table 3.1 below.

Table 3.1: Broad elements selected for the research and suitability for the project (refer to sections in column 1).

Biological Indicators	Justification
Species Records (2.3.2)	- Detailed and useful data relating to protected/notable species used professionally but rarely used in research.
GCN HSI (2.3.2)	- Used by consultancies to determine habitat potential and viability - Is a useful indicator but rarely used in research.
Macroinvertebrate Analysis (2.8.1)	- Standardised and valid Environment Agency Practice. - Parameter in the WFD as it is useful to determine water quality. - Used by researchers for ecological analysis: e.g. Heal (2000); Wenn (2008); Le Viol *et al.* (2009) and Briers (2014).
Botanical Analysis (2.8.2)	- Useful to determine floral diversity and evenness. Used by researcher such as Li *et al.* (2019). Criticised by has no viable alternative.
Physico-Chemical Indicators	**Justification**
pH (2.10.1) and Temperature (2.10.2)	- Parameters in the WFD. - Key baseline used in most water quality papers (e.g. Scholz, 2004).
BOD_5 and DO (2.10.3)	- Parameters in the WFD. - Used by several researchers for chemical and ecological analysis. - Source examples include Mitchell (2005) and Scholz (2004).
Nutrients (2.10.4)	- Parameters in the WFD to address key issues of pollution. - Research includes Mallin and Cahoon (2020) and Jarvie *et al.* (2007).
SP, PS and SS (2.10.5)	- Parameters in the WFD. - Addresses key issues of specific contaminants and is used by many researchers (e.g. Scholz, 2004, Li and Zhang, 2010).

3.3. Aim

To investigate the physico-chemical surface water quality, ecology and biodiversity of a catchment scale afforestation Natural Flood Management project in the Arrow catchment, Warwickshire, UK to construct an understanding of the potential role of such NFM measures in relation to catchment quality and produce a baseline for future research.

3.4. Hypothesis

Null Hypothesis:

The catchment woodland has no significant influence on the physico-chemical surface water quality (pH, temperature, DO, BOD_5, TRP, TN, TA, SP/PS and SS) or the ecology/biodiversity (macroinvertebrate and botanical communities and GCN potential) of the Arrow catchment, Warwickshire.

Alternate Hypothesis:

The catchment woodland has a significant positive influence on the physico-chemical surface water quality (pH, temperature, DO, BOD_5, TRP, TN, TA, SP/PS and SS) or the ecology and biodiversity (macroinvertebrate and botanical communities and GCN potential) of the Arrow catchment, Warwickshire.

3.5. Objectives

1. Review existing literature to investigate current understanding of Natural Flood Management and identify associated research gaps and key methodologies relating to the analysis of Natural Flood Management measures, water quality, ecology and biodiversity.

2. Extract data from past biological records of ecology, biodiversity and physico-chemical water quality conditions to investigate spatial and temporal fluctuations and determine potential catchment improvement.

3. Collect biological data (macroinvertebrates, botanical and GCN HSI) and bi-weekly water samples for physico-chemical analysis (pH, temperature, DO, BOD_5, TRP, TN, TA, SP/PS and SS) across the spring and summer seasons of one hydrological year from strategically placed points across the catchment to assess water quality and ecological community presence and tolerance to pollution.

4. Analyse data using laboratory-based testing methods and GIS processing techniques to construct an understanding of the potential role of afforestation on surface water quality and biodiversity and produce a baseline for future research.

3.6. Research Process

Figure 3.1 outlines the broad research process undertaken for the study. It incorporates the broad processes used for both the primary lab analysis and secondary GIS processing and visualisation methods.

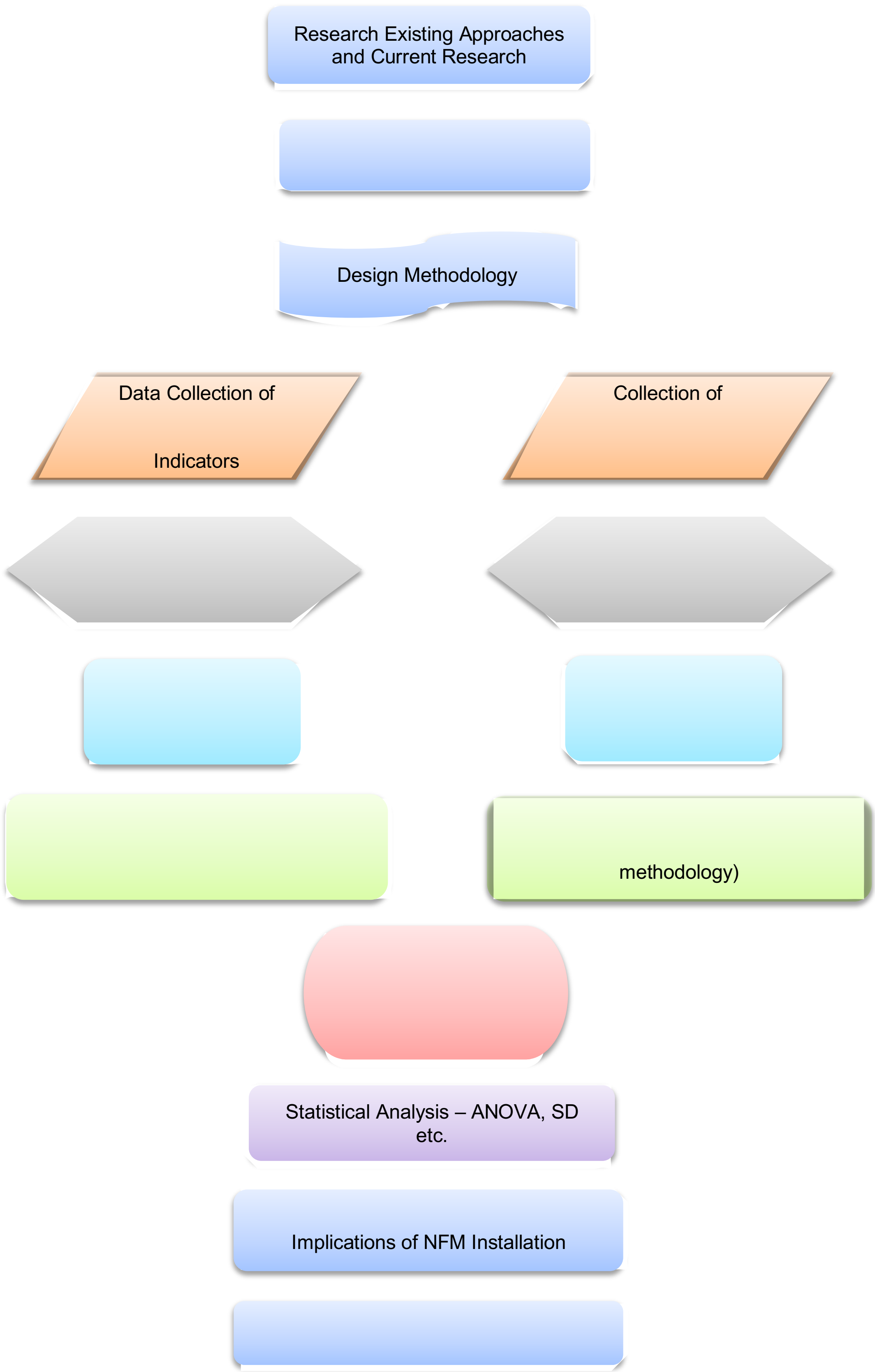

Figure 3.1: Flow diagram of the research process.

3.7 Case Study

3.7.1. Background

This research focused on a case study of the Arrow catchment and the HoEF broadleaved woodland NFM project located within the West Midlands Green Belt in South Warwickshire, UK between Studley and Alcester. The main aim of the NFM project is to plant, protect and preserve a new 120 km^2 broadleaved woodland across south Warwickshire and Worcestershire. A total of 1.8 million trees (c. 40 km^2) have been planted to date to undo the destruction of the UKs broadleaved woodland, create a space for wildlife and reconnect people with the outdoors (HoEF, 2020). Although the project began and remains as a woodland expansion initiative, the project is now also classified as a Catchment/Floodplain Woodland and is used as a method of NFM to hold water upstream and protect Stratford. The project is planted in compartments and contains 214 woodland and pasture compartments dating from 100+ to under 10 years of age, including 58 ha of Ancient Semi-Natural Woodland (ASNW) and 50 ha of Planted Ancient Woodland Sites (PAWS) planted in pre-1900 or in a secondary scheme in 1965. The site contains a total of 1920 ha of planted woodland from 1900-2017, 74% of which was planted from 2002 onwards as part of the NFM scheme.

The scheme also complies with Objective 6 of the Stratford-on-Avon Core Strategy (2011-2031), which outlines requirements for: maintenance or restoration of the flood plain; management of flood risk via catchment management and 'Good' status or potential (Stratford-on-Avon District Council, 2016).

3.7.2. Sample Locations

The project is located within a rural dominated catchment, with some urban runoff influences from nearby Studley, Alcester and Stratford. Catchment conditions were assessed via the collection of freshwater samples and the undertaking of ecological sampling at 11 sample points across the catchment. 2 points were placed within urban areas outside of the NFM, 4 in the river adjacent to the NFM (including 1 adjacent to the WTW), 3 within the main drainage channel and 2 in the artificial ponds to ensure an accurate representation of catchment conditions. Sites were selected after elevation and runoff direction was analysed with a 5 band, 1 m resolution LIDAR composite Digital Terrain Model (DTM) produced in ArcMap software (Figure 3.2). Data for the DTM was collected from the EA (EA, 2019a). A small gap in the 1 m DTM was superimposed with 5 m resolution data from Digimap (2019).

Selected sample sites comprised 6 points along a 5.5 km section of the River Arrow, 3 points along the NFM main drainage channel stretching 1.29 km and 2 ponds located within the NFM. The location of the selected sites in relation to the plantation compartments are shown in Figure 3.3 below. Spatial and Fishbone/Ishikawa schematic diagrams of the NFM and surface water flow direction are shown in Figures 3.4 (a) and (b) respectively. Descriptions of conditions at each of the 11 sites are also provided in Table 3.2 (River Arrow); Table 3.3 (Drainage Channel) and Table 3.4 (Ponds). Compartmental and extent data of the NFM was collected directly from the HoEF (2019).

Digital Terrain Model (DTM) of the Arrow Catchment and NFM

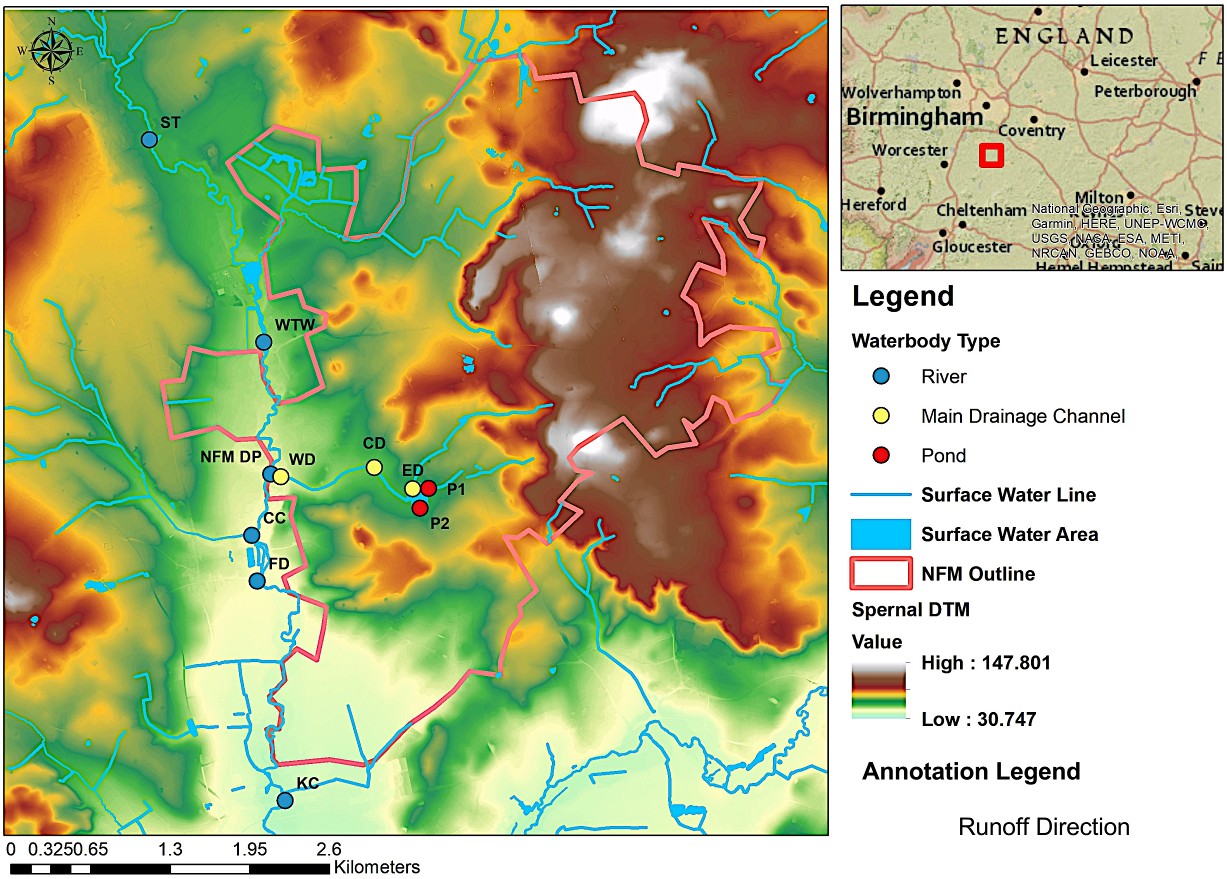

Figure 3.2: Digital Terrain Model of the Arrow catchment and NFM site.

Sample Locations

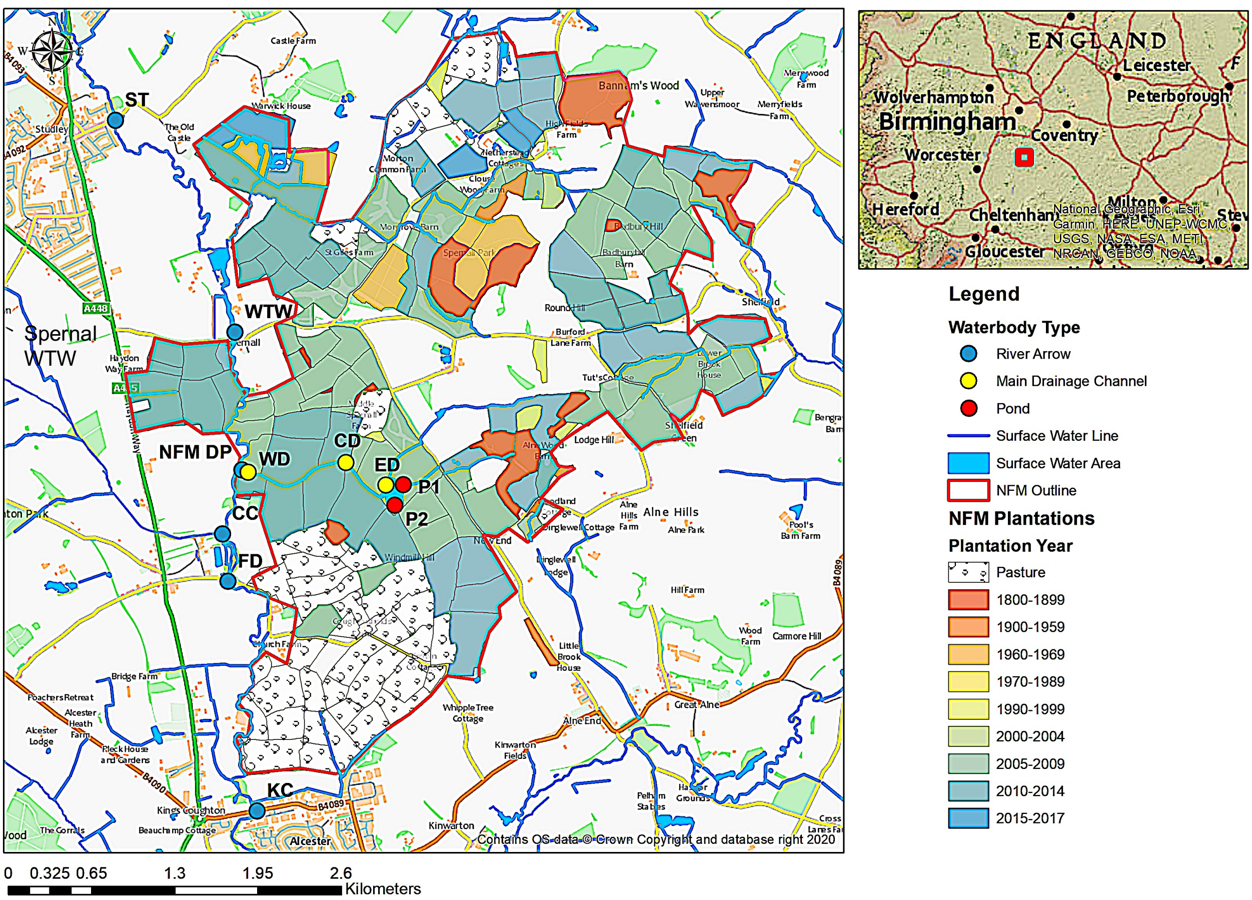

Figure 3.3: Location map of the NFM plantation, age and selected study sites.

NFM Schematic

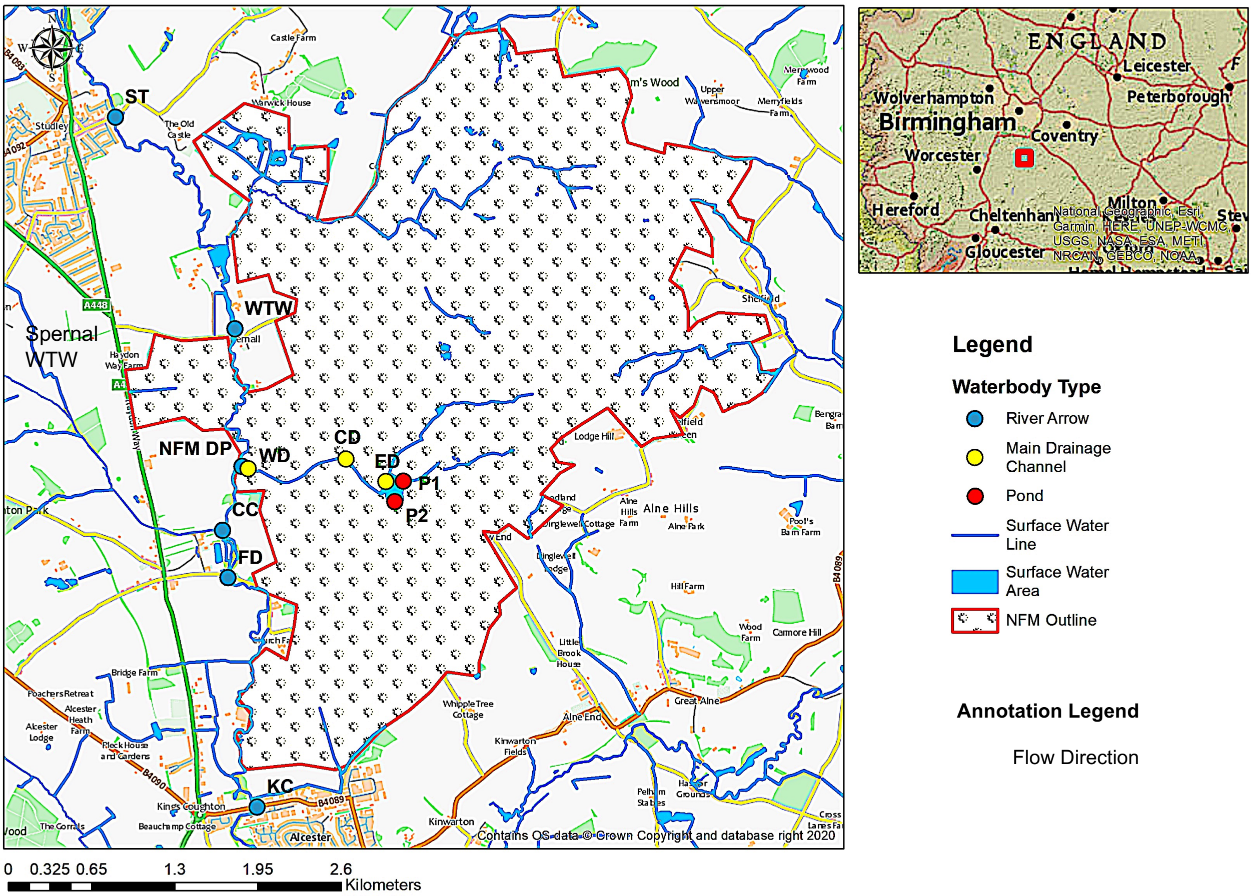

Figure 3.4 (a): Schematic of the NFM runoff and catchment flow direction.

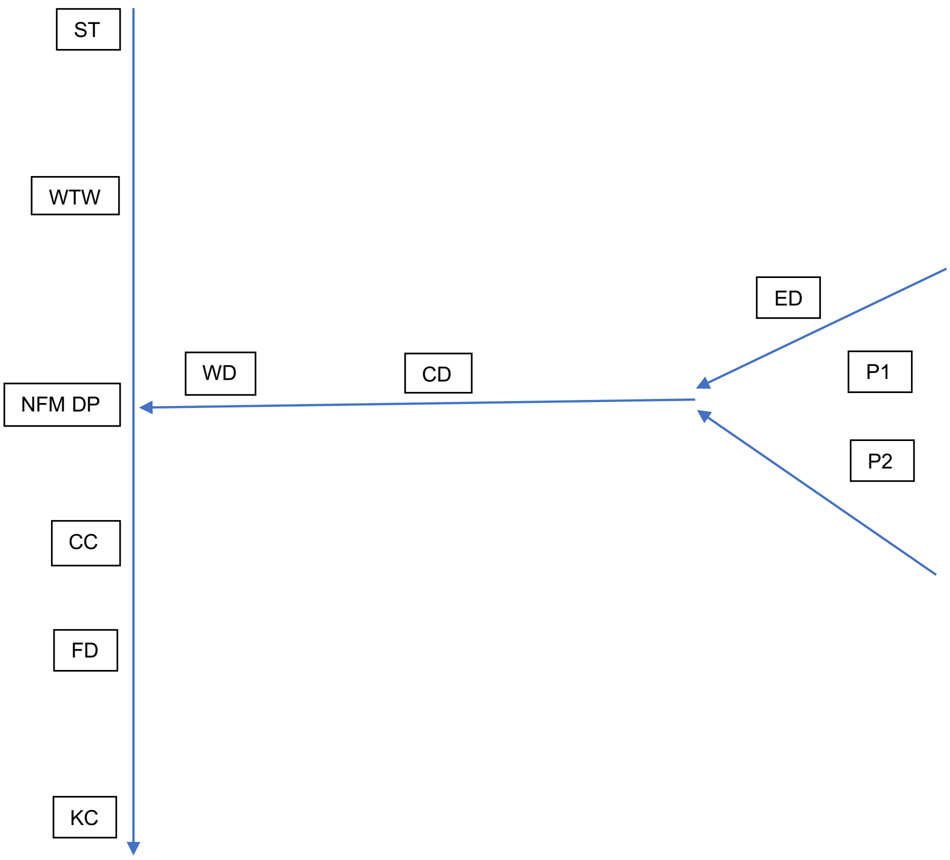

Figure 3.4 (b): Fishbone/Ishikawa diagram of sample sites and flow direction.

Table 3.2: River Arrow site descriptions.

Site Name / Map Ref	OS Grid Ref	Description	Photograph
Studley (ST)	SP 07640 63935	Control site located adjacent to a road bridge in the village of Studley. River measured c. 30-50 cm in depth, with a pebble substrate and c. 45 º banks. Minimal evidence of eutrophication.	
Water Treatment Works (WTW)	SP 08575 62204	Located 380 m south of Spernal water treatment works. River point measured c. 30-50 cm in depth, with a pebble substrate and c. 45 º banks. Significant algae and evidence of severe eutrophication.	
NFM Discharge Point (DP)	SP 08628 61202	Located at the main NFM discharge point into the Arrow, 990 m south of the WTW point. River was shelved from c. 30 cm-2m in depth, with a pebble substrate and banks of c. 80-90 º on the inner edge and shallow banks on the outer. Minimal evidence of eutrophication.	
Coughton Court (CC)	SP 08473 60703	Located within the grounds of Coughton Court (National Trust), 520 m south of NFM DP. River was c. 1-1.5 m in depth, with a silt substrate and large quantities of algae and detritus. Banks were shallow on the inner edge and c. 45 º on the outer. Moderate evidence of eutrophication.	
Ford (FD)	SP 08526 60353	Located adjacent to the concrete ford 350 m south of Coughton Court. River was c. 30-50 cm in depth, with a pebble, silt and cobble substrate. River had banks of c. 45 º with minimal algae and evidence of eutrophication.	
Kings Coughton (KC)	SP 08735 58548	Control site located adjacent to a road bridge in the village of Kings Coughton c. 300 m south of the plantation edge. River point was c. 30 – 50 cm in depth, with a pebble and silt substrate and banks of c. 45 º. Moderate algae and evidence of eutrophication.	

Table 3.3: Main NFM Drainage Channel site descriptions.

Site Name / Map Ref	OS Grid Ref	Description	Photograph
Eastern Extent of Main Drainage Channel (ED)	SP 09762 61092	Located c. 400 m east of the central point of the channel and c. 100 m east of a small concrete bridge, where water attenuated. Point was c. 5 cm in depth and c. 30 cm in width, with pebble and mud substrate and a steep bank of c. 80 °. No algae/eutrophication.	
Central Extent of Main Drainage Channel (CD)	SP 09449 61261	Located in the centre of the channel prior a small concrete bridge where water attenuated. Point ranged from c. 10-20 cm (attenuated) and c. 5 cm (flowing stream) depth with a width of c. 50 cm. Point had a pebble and mud substrate with a bank of c. 70 °. No algae/eutrophication.	
Western Extent of Main Drainage Channel (WD)	SP 08626 61211	Located c. 600 m west of the central point of the channel and c. 100 m from the discharge point into the River Arrow. Channel measured c. 15 cm in depth and c. 1 m in width with a pebble, silt and mud substrate and banks of c. 60 °. No algae/eutrophication	

Table 3.4: Pond site descriptions.

Site Name / Map Ref	OS Grid Ref	Description	Photograph
Pond 1 (P1)	SP 09833 61086	Located in the east of the NFM adjacent to the drainage channel. P1 comprised a small pond manually made by the Environment Agency. P1 measured c. 5,500 m^2 with shallow banks, a clay substrate and minimal – moderate aquatic and terrestrial vegetation. Minimal eutrophication.	
Pond 2 (P2)	SP 09771 60976	Located in the east of the NFM adjacent to P1, P2 comprised a scrape manually made by the HofE Forest, with a small central island. P2 measured c. 15,000 m^2 with shallow banks, a clay substrate, minimal aquatic vegetation and extensive terrestrial vegetation. Minimal eutrophication.	

3.8. Primary Data

The research for this project predominantly encompassed the collection of a primary dataset, which included a pilot study in March 2019 to assess feasibility. To analyse water quality, water samples were taken twice per month for a duration of 6 months. Samples were taken from 11 sites located upstream, adjacent to and downstream of the contrasting woodland sections. However, a total of 127 samples were taken as opposed to the 132 expected, as 3 sites were not initially included in the pilot study and the ford (FD) was inaccessible in August due to construction. For ecological analysis, an investigation of the riparian vegetation structure and species composition was undertaken within the optimal summer sampling period as floral species are best identified in this period. Standard macroinvertebrate sampling (integrated 3-minute kick sample) was also completed within the required spring and autumn periods (WFD-UKTAG, 2013). Samples collected include rainstorm events of varying magnitude, as these may have differing severity and differing recovery lag time in terms of sediment loading between sampling locations. Table 3.5 details the exact primary methodology of this research project.

Table 3.5. Methodology for primary data collection.

<table>
<tr><th colspan="2">Indicator / Field Test</th><th>Method of collection (Objective 2)</th><th>Equipment (Objective 2)</th><th>Sample Period / Date</th></tr>
<tr><td rowspan="2">Physico-Chemical Water Quality</td><td>DO and Temperature</td><td>O_2 Meter
(also used for temperature)</td><td>(OXI 197, WTW, 82362 Weilheim, Germany)</td><td rowspan="2">March – August 2019
- 20/03/19
- 27/03/19
- 03/04/19
- 10/04/19
- 08/05/19
- 23/05/19
- 21/06/19
- 28/06/19
- 12/07/19
- 26/07/19
- 08/08/19
- 29/08/19</td></tr>
<tr><td>Physico-Chemical Analysis</td><td>2 Litres of water collected from 11 sites at bi-weekly intervals for 6 months.</td><td>Sterile 1L plastic bottles</td></tr>
<tr><td colspan="2">Macroinvertebrates</td><td>Standard 3-minute kick sample in accordance with the standard BS EN 27828:1994, ISO 7828-1985 for the rivers and main drainage channel and BS EN ISO 9391:1995, BS 6068-5.15:1995 for the ponds.</td><td>Sample net (1mm mesh)</td><td>Spring - 17/04/19
Autumn – 19/08/19 & 23/08/19</td></tr>
<tr><td colspan="2">Great Crested Newt Habitat Suitability Index (GCN HSI)</td><td>Field survey:
ARG UK HSI Assessment (ARG UK, 2010)</td><td>No apparatus required</td><td>10/04/2019</td></tr>
<tr><td colspan="2">Botanical Sampling</td><td>Field survey</td><td>0.5 x 0.5 m Quadrat</td><td>24/07/2019</td></tr>
</table>

3.9. Secondary Data

Water quality monitoring data of the Arrow catchment for Cycle 1 (2009-2014) and Cycle 2 (2015-2021) of river basin planning under the WFD was obtained from the Environment Agency (2020) to construct a baseline for this research and determine the water quality of the catchment prior to the existence of the HoEF NFM plantation. As Cycle 2 was still active, 2016 was the latest available published dataset. NFM plantation data was provided by the HoEF (2019). Secondary desk-based information was also collected from Warwickshire Biological Records Centre in April 2019 to determine spatial and temporal floral/faunal species presence within the Arrow catchment. This data was then visualised using the Geographical Information System software ArcMap. Figure 3.5 outlines the process of data capture and visualisation for all ArcGIS maps in this project.

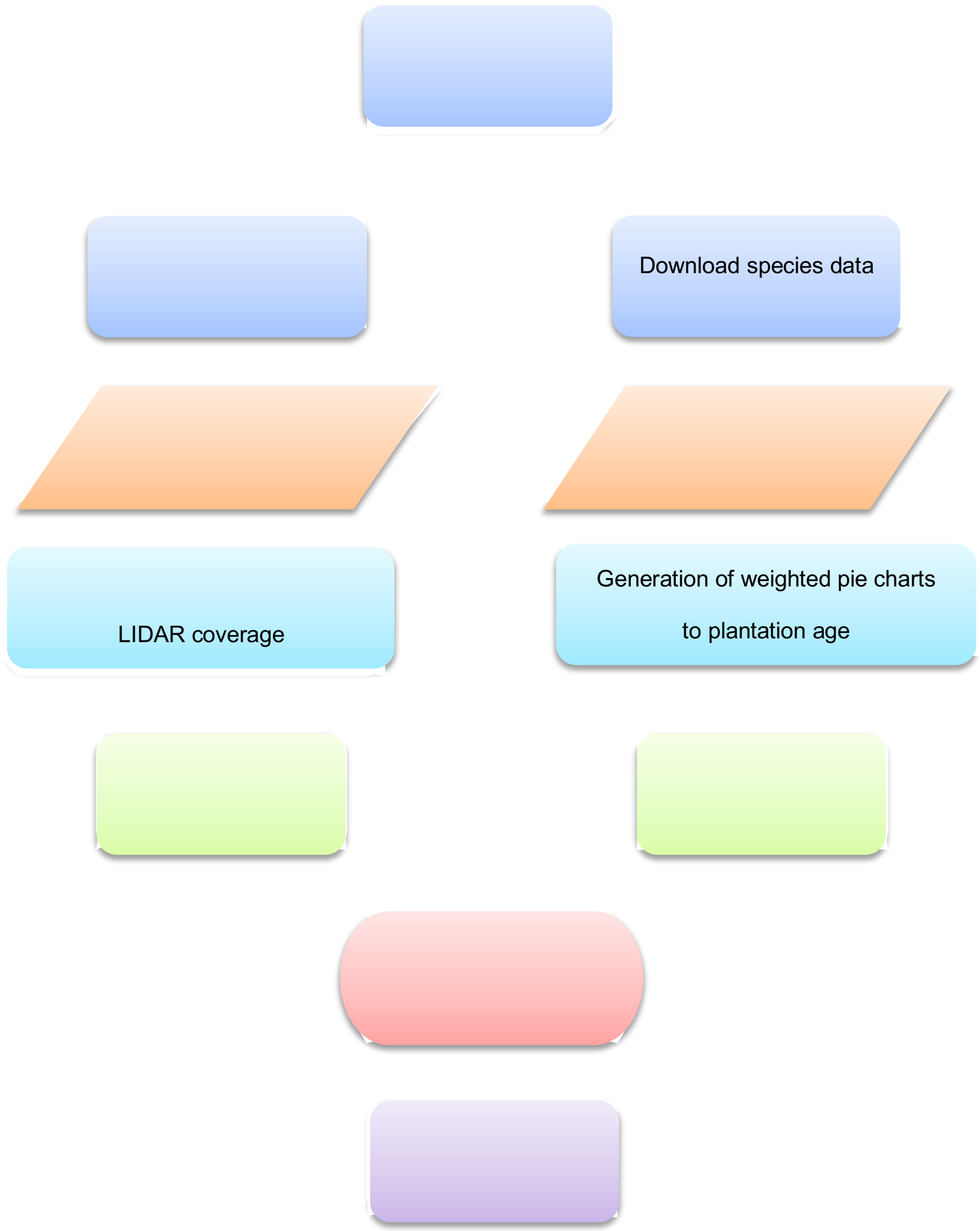

Figure 3.5: The process of data capture and visualisation in ArcMap for GIS processed maps.

3.10. Methods of Analysis

Following collection, samples were subject to several laboratory based analytical tests to determine the ecological and physico-chemical quality of the catchment. The analytical methodologies used to assess physico-chemical and biological health are outlined in Table 3.6 and 3.7 respectively.

Table 3.6: Laboratory equipment and procedures for each analyte used for the study.

Indicator	Method of Analysis (Objective 3)	Equipment (Objective 3)	Method Reference
pH	pH meter	(Fisherbrand Accumet AE150, Fisher Scientific, Leicestershire, UK)	(WFD-UKTAG, 2013)
Biochemical Oxygen Demand (BOD_5)	Winkler method: BOD_5 (5-day incubation) at 20ºC with aeration and a magnesium chloride ($MnCl_2$) and potassium iodide (KI) / potassium hydroxide (KOH) seal. Released by conc. hydrochloric acid (HCl) followed by a 100 ml sodium thiosulphate ($Na_2S_2O_3$) titration.	50 ml Burette / 100 ml Bulb Pipette	(Winkler, 1888)
Total Reactive Phosphorus (PO_4) (TRP)	Flow Injection Analysis (FIA)- Phosphomolybdenum blue colorimetric method: Aqueous orthophosphate combined with ammonium molybdate ($(NH_4)2MoO_4$) to form a blue colour.	(SOFIA FIASTAR 5000, Foss, Höganäs, Sweden)	(BS EN ISO 15681-1:2003) AN 5240: (Foss, n.db)
Total Nitrate (TN) (Sum NO_3^- and NO_2^-)	Flow Injection Analysis (FIA) - Nitrate (NO_3^-) reduced to nitrite (NO_2^-) by cadmium reduction and determined as a purple azo dye at 540 nm following diazotisation with sulphanilamide ($C_6H_8N_2O_2S$) / coupling with NED·2HCl*.		(BS EN ISO 13395: 1996) AN 5210 (Foss, n.da)
Total Ammonia (TA) (NH_4)	Flow Injection Analysis (FIA) - Aqueous ammonia is injected into a carrier of boric acid (H_3BO_3) and EDTA* ($C_{10}H_{16}N_2O_8$) and merged with sodium hydroxide (NaOH). Gaseous ammonia diffused through a membrane into acidic indicator (sodium dihydrogen phosphate (NaH_2PO_4) / indicator powder).		(BS EN ISO 11732: 2005) AN 5220 (Foss, n.dc)
Specific Pollutants and Priority Substances (SP/PS)	Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES). Pollutants analysed comprised: Cd, Cu, Ni, Zn, Pb, Fe, Co, K, Na, Ca, As, Cr and Mn. Multi element standards were used with appropriate wavelengths.	(ICP-OES Optima 8300, Perkin Elmer, Massachusetts, USA)	(WFD-UKTAG 2013c; WFD, 2000/60/EC)
Suspended Sediment (SS)	500ml of each sample was filtered and oven dried overnight at 80ºC prior to weight measurement.	Whatman 0.45 glass fibre filter paper	(Scholz, 2004; WFD-UKTAG, 2013b)
NED·2HCl: N-(1-naphthyl)ethylenediamine dihydrochloride; EDTA: Ethylenediaminetetraacetic Acid			

Table 3.7: Methods of Analysis for Biological Indicators.

Indicator	Method of Analysis (Objective 3)	Method Reference
GCN HSI	ARG UK HSI assessment methodology:	(ARG UK, 2010)
Macroinvertebrates	Family level ID with 70% ethanol preservation and microscope. Analysis with Whalley, Hawkes, Paisley and Trigg (WHPT) in River Invertebrate Classification Tool (RICT), Shannon Wiener's Index of Diversity (H') and Pielou's Evenness Index (J')	WFD-UK TAG (2014); Shannon and Weaver (1949); Pielou (1966)
Botanical Diversity	Analysis with Shannon Wiener's Index of Diversity (H') and Pielou's Evenness Index	Shannon and Weaver (1949); Pielou (1966)

3.11. Calibration of Laboratory Equipment

To ensure accuracy and reliability of the data produced, each instrument used to analyse samples was frequently calibrated with the use of standards. The calibration methodology is outlined in Table 3.8.

Table 3.8: Equipment calibration methodology using standards and R^2 calibration values for each standard.

Indicator	Calibration Method	Standard concentrations	R^2 Value of standards
BOD_5 / SS	Autopipette/scale calibration (1ml water = 1g)	N/A	N/A
pH	Calibration to two standards	pH 4; pH 7	N/A
TRP	6-7 100ml standards of working ranges 0.005 - 1mg/l (LR) and 0.1-10mg/l (HR) in accordance with BS EN ISO 15681-1:2003.	LR (mg/l): 0.005; 0.01; 0.03; 0.05; 0.1; 0.5; 1	0.999 (L)
		HR (mg/l): 0.1; 0.2; 0.3; 0.5; 5, 10	0.999 (NL)
TN	6 100ml standards of working range 0.1-10mg/l (HR) in accordance with BS EN ISO 13395:1996.	HR (mg/l): 0.1; 0.5; 1; 2; 5; 10	1.000 (NL)
	50% dilution used for samples > 10mg/l.		1.000 (NL)
TA	5 100 ml standards of working ranges 0.01-1mg/l (LR) and 1-10 mg/l (HR) in accordance with BS EN ISO 11732: 2005.	LR (mg/l): 0.01; 0.05; 0.1; 0.5; 1	0.999 (L)
		HR (mg/l): 1; 2; 5; 7; 10	1.000 (NL)
SP / PS	6 multi-element 100ml standards for ranges 0.1-15mg/l. Made with 1000mg/l stock of each element. Elements: Cd, Cu, Ni, Zn, Pb, Fe, Co, K, Na, Ca, As, Cr and Mn.	1: 0.1 All, 1 Ca 2: 0.25 Fe, 0.5 K/Na, 2.5 Ca 3: 0.5 Fe, 1 K, 2 Na, 5 Ca 4: 1 Fe, 2 K, 5 Na, 10 Ca 5: 2 Fe, 3 K, 7.5 Ca 6: 3 Fe, 15 Ca	9 elements: 1.000 (L) Fe: 0.999 (L) K: 0.998 (L) Na: 0.999 (L) Ca: 0.999 (L)

L: Linear; NL: Non-Linear. Refer to Appendix B for full polynomial regression charts of the calibrations.

3.12. Biological Analysis Methodology

3.12.1. Desk Study – Spatial and Temporal Species Presence and Distribution

A desk study of designated sites within 2km of the NFM boundary and species recorded within 1km of the NFM boundary was conducted in April 2019 by the Warwickshire Wildlife Trust (WWT) (WWT, 2019) as outlined in Section 3.9.

3.12.2. GCN HSI Assessment

The GCN HSI can be used as a useful indicator for amphibian species potential in artificial ponds. Originally developed by Oldham *et al* (2000), the HSI is a numerical index between the values of 0 and 1, in which values closer to 0 indicate unsuitable habitat and values closer to 1 indicate optimal habitat (ARG UK, 2010). After calculation, the resulting HSI score calculated with Eq. (1) is converted to a suitability classification for GCN as per the parameters outlined in Table 3.9.

Table 3.9: HSI scoring parameters and subsequent pond suitability for GCN (ARG UK, 2010).

HSI Score	Pond Suitability
<0.5	Poor
0.5-0.59	Below Average
0.6-0.69	Average
0.7-0.79	Good
>0.8	Excellent

3.12.3. Botanical Diversity and Evenness

Botanical diversity was determined using the Shannon Wiener Index of Diversity (H’) calculated with Eq. (2) (Shannon and Weaver, 1949). The index typically calculates between the values of 1.5 and 3.5, and rarely surpasses the 4.5 value of even distribution (Bibi and Ali, 2013). The use of Shannon’s Index was used in combination with the linked Pielou’s Evenness Index (J’) calculated with Eq. (3) and Eq. (4) (Pielou, 1966) to construct a complete representation of diversity.

3.12.4. Macroinvertebrates

Macroinvertebrate communities are extremely sensitive to pollution as a number of species (such as some families of Trichoptera and Ephemeroptera) are only able to survive in pristine water conditions. Therefore, the relative abundance and EQR (Ecological Quality Ratio) for Number of Taxa (NTAXA) and Average Score Per Taxon (ASPT) were calculated to reflect macroinvertebrate presence can be used to infer water quality. The assessment of EQR scores produced by the RICT methodology is also a WFD-UKTAG/ WFD requirement. The benthic invertebrate fauna boundary values are outlined in Table 3.10.

Table 3.10: Benthic Invertebrate Fauna Boundary Values (WFD-UKTAG, 2013a).

WHPT in RICT		
Status	**EQR NTAXA**	**EQR ASPT**
High	0.80	0.97
Good	0.68	0.86
Moderate	0.56	0.72
Poor	0.47	0.59

3.13. Physico-Chemical Analysis Methodology - WFD-UKTAG and WFD Classification

This project classifies the quality status for 9 water quality indicators in accordance with the methods and status classifications as outlined by the UK Technical Advisory Group (WFD-UKTAG) under the WFD (2000/60/EC). However, the classifications within this research are based on 6-months of data as opposed to the 12 outlined, as this was not possible in the project timeframe. The status classifications are High, Good, Moderate, Poor and Bad, where "High" refers to the boundary between High and Good, Good refers to the boundary between Good and Moderate, and so on. To achieve High Status, the standard must be bettered or equalled. The coding used for quality and status is outlined in Table 3.11.

Table 3.11: Quality coding for WFD status and maximum average tolerance values

WFD Status Coding					**Threshold Values**	
High	Good	Moderate	Poor	Bad	< Threshold	> Threshold
H	G	M	P	B	< Max Average	> Max Average

As the Arrow catchment is below an 80 m elevation and averaged at 100-250 mg/l $CaCO_3$, the standards for waterbody Type 5 or 7 (cyprinid, lowland, high alkalinity) were applied where applicable (UKTAG, 2008).

3.13.1. Acid Conditions – pH

pH acts as in indicator for natural and anthropogenic acidification and can be influenced by various factors however, in the case of this system, these factors are not highly variable. pH is also an indicator for labile aluminium, which is believed to provide the toxicity that shapes ecological communities at low pH (WFD-UKTAG, 2014c). Therefore, standards were devised by the WFD-UKTAG (2014) under the WFD (Table 3.12). The boundary for good and moderate was placed at the point labile aluminium increases to concentrations in which it begins to degrade ecological communities.

Table 3.12: Acid Condition standards for rivers (WFD-UKTAG, 2014c).

pH				
(Annual Mean)				
Type**	High	Good	Moderate	Poor
Clear	6.6	5.95	5.44	4.89
**A concentration of 10 mg/l Dissolved Organic Carbon (DOC) is used as a threshold between clear and humic water. As the Arrow catchment averages below 10 mg/l, the standards for clear water are used.				

3.13.2. Temperature

Water temperature directly affects the survival of aquatic species by influencing growth and development, toxic substance toleration, reproduction ability and resistance to disease. Temperature can also indirectly shift water chemistry by altering the solubility and metabolic consumption of oxygen. Aquatic species prefer particular temperature ranges with a tolerance to small changes. Therefore, the following standards (Table 3.13) were implemented by the WFD-UKTAG (2008).

Table 3.13: Temperature standards for rivers (WFD-UKTAG, 2008b).

Temperature (°C)				
(98 Percentile)				
Type	High	Good	Moderate	Poor
3, 5 and 7	25	28	30	32
'98 Percentile' = Standard is failed if the measured value of the parameter is less than the standard 2% of the time.				

3.13.3. Dissolved Oxygen (DO)

Dissolved oxygen is an essential indicator for water quality as plentiful available O_2 is fundamental for the survival of aquatic life. Enhanced microbial activity caused by additions of organic matter such as sewage effluents, stormwater runoff and agricultural runoff reduce the amount of O_2 available for aquatic life and threaten populations (UKTAG, 2008). Therefore, standards and targets for environmental quality were set by the WFD-UKTAG for the WFD and are displayed in Table 3.14.

Table 3.14: Dissolved oxygen standards for rivers (WFD-UKTAG, 2008a).

Dissolved oxygen (% Saturation)				
(10 Percentile)				
Type	High	Good	Moderate	Poor
3, 5 and 7	70	60	54	45
'10-Percentile' = Standard is failed if the measured value of the parameter is less than the standard 10% of the time.				

3.13.4. Biochemical Oxygen Demand (BOD_5)

Biochemical oxygen demand is one of the oldest and most widely used criteria for the evaluation of biodegradation of chemicals and wastewater substances and refers to the readily biodegradable fraction of the organic load in water (Jouanneau *et al.*, 2014). High BOD_5 values (>14) indicate a high level of microbial oxidation of waste matter, resulting in a high level of oxygen use and a poor quality, where a lower value (<4) indicates a high quality (Penn, Pauer and Mihelcic, 2009). The diminished available oxygen causes present communities to begin to perish and results in a waterbody unable to support aquatic biota as the competition for oxygen is too high for the survival of wildlife (WFD-UKTAG, 2008a). Although updated targets and standards for BOD_5 were set by the WFD-UKTAG (2014c) for the WFD to assess oxygen quality (Table 3.15), this index is not used in the overall status of a waterbody.

Table 3.15: BOD_5 standards for rivers (WFD-UKTAG, 2014c).

Biochemical Oxygen Demand (mg/l)				
(99 Percentile)				
Type	High	Good	Moderate	Poor
3, 5 and 7	9	11	14	19
'99 Percentile' = Standard is failed if the measured value of the parameter is more than the standard 1% of the time.				

3.13.5. Total Reactive Phosphorus (TRP)

As a plant nutrient, excessive phosphorus enrichment has been directly attributed to harmful algal bloom stimulation. Accelerated growth of bacteria, phytoplankton, macroalgae and other flora trigger eutrophication of rivers, streams and lakes across the world. The increased concentration of bacterial and algal communities exerts a significant BOD on affected waterbodies and degrade habitat conditions. The subsequent imbalance of communities often causes pre-existing communities to perish (Mallin and Cahoon, 2020). In response, TRP standards were implemented to mitigate impacted waterbodies and indicate likelihood of improvement (WFD-UKTAG, 2013c). The standards calculated for the Arrow catchment with Eq. (5) / Eq. (6) are shown in Table 3.16.

Table 3.16: Calculated Annual Mean TRP Standards for the River Arrow Catchment WFD-UKTAG (2013c).

Total Reactive Phosphorus (µg/l)			
(Annual Mean)			
Status	**Standard 1**	**Standard 2**	**Standard 3**
High	44	41	41
Good	82	77	77
Moderate	198	189	189
Poor	1060	1041	1040
Reference Conditions – Based on DTM Elevations (S3: Figure 3.2) and Environment Agency Alkalinity Data (EA, 2020d) Standard 1: River (ST); Drainage Channel (ED, CD); Ponds (P1, P2). 60 m Altitude, 238 mg/l $CaCO_3$ Alkalinity Standard 2: River (WTW, NFM DP, CC, F); Drainage Channel (WD). 50 m Altitude, 184 mg/l $CaCO_3$ Alkalinity Standard 3: River (KC). 45 m Altitude, 175 mg/l $CaCO_3$ Alkalinity			

3.13.6. Total Nitrate (TN)

As nitrate is also a nutrient, it causes excessive algal growth and eutrophication. Nitrate is mainly caused by diffuse pollution from agricultural runoff, which woodland NFMs could potentially mitigate, however, it is also discharged by point sources such as WTWs. Although there is currently no standard in relation to nitrate within the WFD, it is controlled by the Nitrates Directive (91:676:EEC) (1991) in which it states that rivers above 25 mg NO_3/l are considered to be of concern and a 50 mg NO_3/l maximum limit has been implemented. The Arrow catchment is also located within a Nitrate Vulnerable Zone (NVZ) (EA, 2020b) which are areas containing high levels of nitrate and agricultural pollution.

3.13.7. *Total Ammonia (TA)*

Ammonia is a decay product of nitrogenous organic waste and is most hazardous for its toxicity and sub-lethal impacts on aquatic biota (WFD-UKTAG, 2008a). Although the toxicity of ammonia is mainly attributable to the un-ionised NH_3 particulate, the chronic risk of both the un-ionised and ionised NH_4^+ form is considered great (Zhang *et al.,* 2018). Ammonia also contributes to soil acidification and eutrophication of waters (EU, 2010). The standards implemented by the WFD-UKTAG under the WFD to control ammonia are outlined in Table 3.17.

Table 3.17: Total Ammonia standards for rivers (WFD-UKTAG, 2014c).

Total Ammonia (mg/l)				
(99 Percentile)				
Type	High	Good	Moderate	Poor
3, 5 and 7	0.7	1.5	2.6	6
99 Percentile' = Standard is failed if the measured value of the parameter is more than the standard 1% of the time.				

3.13.8. *Specific Pollutants (SP) and Priority Substances (PS)*

Specific Pollutants (UK) and Priority Substances (EU) are toxic substances discharged in significant quantities into the river and water systems. UK specific pollutants were selected by the WFD-UKTAG and standards to control SP and PS were implemented. Pollutants for analysis in the study were selected from historical presence records (EA, 2020a), laboratory possibility/availability and other literature. The pollutants/elements in the catchment comprised: Cadmium (Cd), Copper (Cu), Nickel (Ni), Zinc (Zn), Lead (Pb), Iron (Fe), Cobalt (Co), Potassium (K), Sodium (Na), Calcium (Ca), Arsenic (As), Chromium (Cr) and Manganese (Mn). Standards for the key pollutants in the Arrow catchment are outlined in Table 3.18 (WFD-UKTAG, 2013b).

Table 3.18: Specific pollutant standards (WFD-UKTAG, 2013b).

Site	**Cd (PS)**	**Cu* (SP)**	**Ni* (SP)**	**Zn* (SP)**	**Pb (PS)**	**Fe (SP)**	**As (SP)**	**Cr III (SP)**	**Mn* (SP)**
AA (µ/l) 95 Percentile	C4 :0.15 C5: 0.25	1	4*	10.9 + ABC 14	1.2	1	50	4.7	123
MT (µ/l)	C4: 0.9 C5: 1.5	-	34*	-	14	-	-	32	-
AA: Annual Average; MT: Maximum Tolerance; 95 Percentile' = Standard is failed if the measured value of the parameter is more than the standard 5% of the time. *: Bioavailable (the fraction of the dissolved concentration of pollutants likely to result in toxic effects- UKTAG Metal Bioavailability Assessment Tool); ABC: Ambient Background Concentration (Avon: 3.1 µg/l); C4: Class 4 – 100-200 mg/l $CaCO_3$; C5: Class 5: >200 mg/l $CaCO_3$									

3.13.9. *Suspended Solids*

Suspended solids (SS) can cause a reduction in light penetration, scouring of riverbeds and in slow flowing conditions fill spaces between gravel and reduce dissolved oxygen. Suspended solids can also absorb heavy metals and transport toxic pollutants. Although the Freshwater Fish Directive provides a guideline standard of an annual mean of 25mg/l, which EU member states are encouraged to endeavour to respect, no imperative standard exists (WFD-UKTAG, 2013b).

3.14. Method Equations

3.14.1. Great Crested Newt Habitat Suitability Index Assessment

The GCN HSI represents the geometric mean of ten indices (factors likely to impact suitability such as pond size and shading). HSI scores were calculated using Eq. (1) (ARG UK, 2010) where SI_n represents each index. As both ponds exceeded 2000m^2, the SI_2 indices (pond size) was omitted and the equation modified to reflect 9 indices:

$$(SI_1 \ x SI_3 \ x SI_4 \ x SI_5 \ x SI_6 \ x SI_7 \ x SI_8 \ x SI_9 \ x SI_{10})^{1/9} \qquad \text{Eq. (1)}$$

3.14.2. Diversity Index Equations

Diversity for macroinvertebrates and botanical species was calculated with Shannon Wiener's Index of Diversity (H'). H' was calculated with Eq. (2):

$$H' = -\sum Pi \ ln \ Pi \qquad \text{Eq. (2)}$$

where H´ = Diversity Index; Pi = the proportion of each species in the sample; ln = natural logarithm.

Evenness was calculated with Pielou's Evenness (J'). J' was calculated with Eq. (3).

$$J' = H' / H' \ max \qquad \text{Eq. (3)}$$

where J' = Pielou; H' = Diversity Index score; H' max = maximum possible value of H'

H' Max was calculated with Eq. (4).

$$H' \ max = ln \ S \qquad \text{Eq. (4)}$$

where ln = Natural Logarithm; S = Number of Species

3.14.3. Phosphate Standards

Phosphate (P) standards for the catchment were calculated with Eq. (5) and Eq. (6) in accordance with the WFD-UKTAG (2014c) recommendations and the WFD (refer to Section 3.13.5).

$$Standard = 10^{\wedge}((1.0497 \ x \ log10 \ (EQR)+1.066) \ x \ (log10 \ (reference \ condition \ RP) - log10(3{,}500)) + log10(3{,}500)) \qquad \text{Eq. (5)}$$

where EQR = Ecological Quality Ratio (universal values set by WFD-UKTAG (2014c) - High = 0.702; Good = 0.532; Moderate = 0.356; Poor = 0.166); Reference Condition RP = the reactive phosphorus concentration at near natural conditions.

$$\textit{Reference condition RP} = 10^{(0.454\,(\log10alk) - 0.0018\,(altitude) + 0.476)} \quad \text{Eq. (6)}$$

where log10alk = log10(alkalinity) = alkalinity concentration of $CaCO_3$ in mg/l; altitude = altitude above mean sea level in m.

3.15. Statistical Analysis

All statistics were processed in SPSS Statistics. Descriptive statistics were used to summarise and simplify data collected. Values calculated comprised Standard Deviation, Mean and spring/summer averages. Charts also contain standard error bars (+/- 1 SE).

Inferential statistics were also implemented to an alpha significance value of $\alpha = <0.05$ to investigate the hypothesis. Significant results are marked as follows: *Significant to $\alpha = 0.05$; **Significant to $\alpha = 0.01$ and ***Significant to $\alpha = 0.001$.

Data was initially tested with the Kolmogorov–Smirnov Test to determine normality and as all datasets contained non-normal distributions, appropriate non-parametric methods were applied. Kruskal-Wallis and Dunn Multiple Comparisons Post-Hoc testing were applied to analyse significant differences in quality across the catchment, with the exception of the analysis between the two ponds, in which Mann-Whitney-U was applied. To analyse seasonal variation Mann-Whitney-U tests were applied to non-normally distributed datasets. Spearman's rank correlation coefficient was also applied to detect relationships between ecological and physico-chemical indicators.

CHAPTER 4. RESULTS AND ANALYSIS

4.1. Introduction

This chapter investigates the ecological value and physico-chemical composition of the NFM surface water and the surrounding catchment. The chapter aims to highlight key observations and analytical findings to infer whether an impact on the catchment's ecology exists in relation to the presence of the NFM.

4.2. Biological Indicators

4.2.1. Desk Study – Spatial and Temporal Species Presence and Distribution

Desk study records identified Bannam's Wood Site of Special Scientific Interest (SSSI), Local Wildlife Sites (LWS), Ecosites, Ancient Semi-Natural Woodland (ASNW) and Ancient Replanted Woodland (ARW) in proximity to the site. Species records comprised notable species presence from 1800-2019 within 1km of the NFM. Figures 4.1(a) and (b) demonstrate species presence prior to and after the commencement of the main plantations respectively. Figures 4.2 (a) and (b) demonstrate total species at each point and the recorded date of each point respectively.

Species Presence in the Arrow Catchment Prior to the Commencement of the Main NFM Plantations

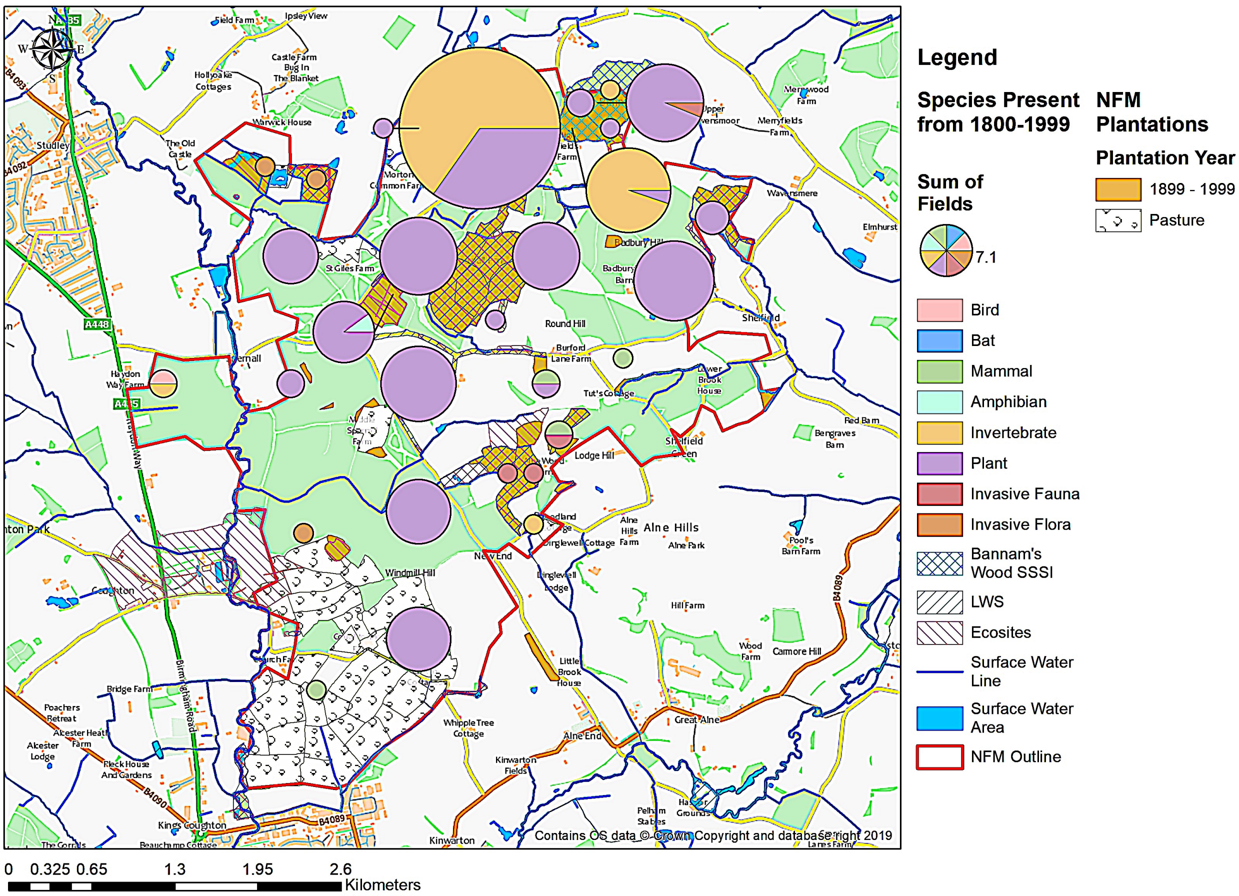

Figure 4.1 (a): Number of records and population (represented by proportional pie charts) from 1800-1999.

Species Presence in the Arrow Catchment After the Commencement of the Main NFM Plantations

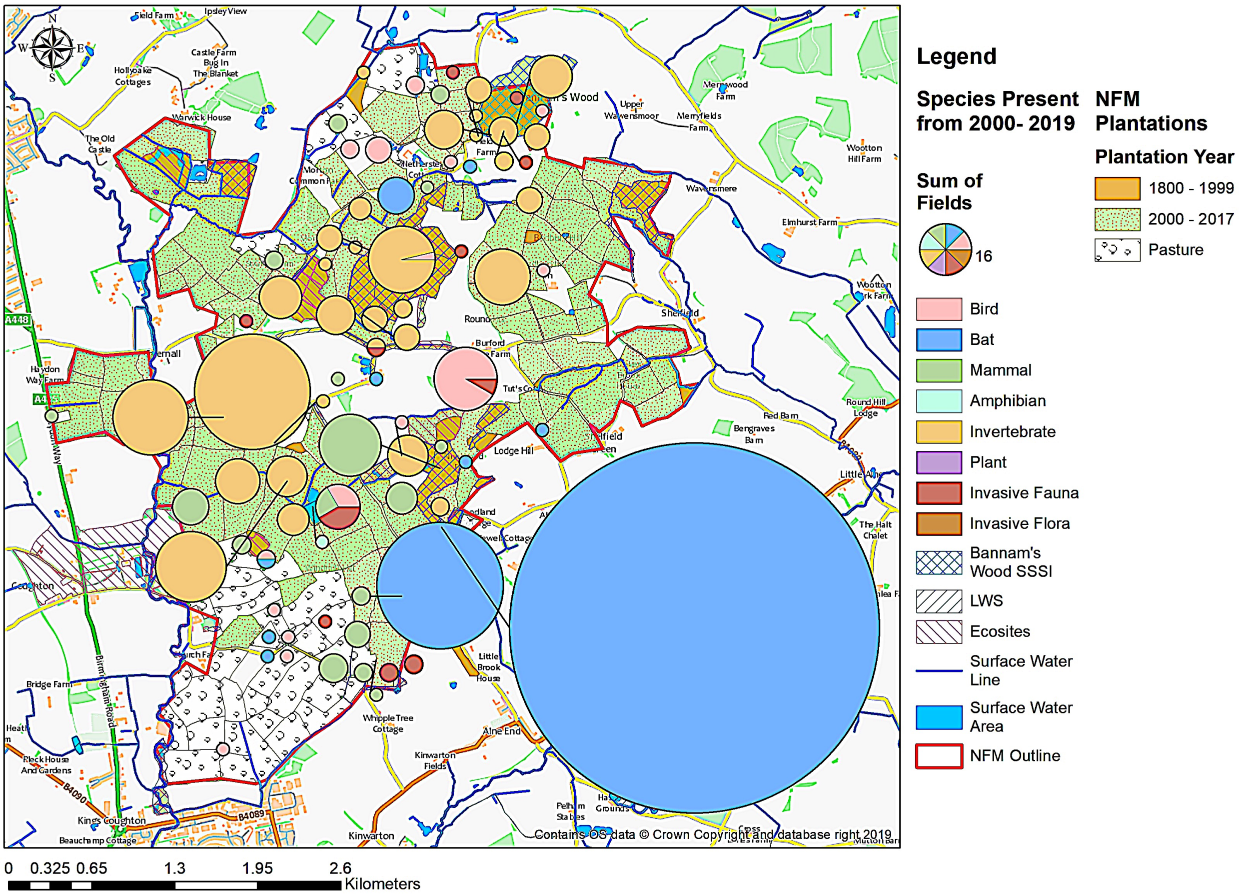

Figure 4.1 (b): Number of records and population (represented by proportional pie charts) from 2000-2019.

Species Presence in the Arrow Catchment Over Time - Totals Prior to and After Commencement of the NFM

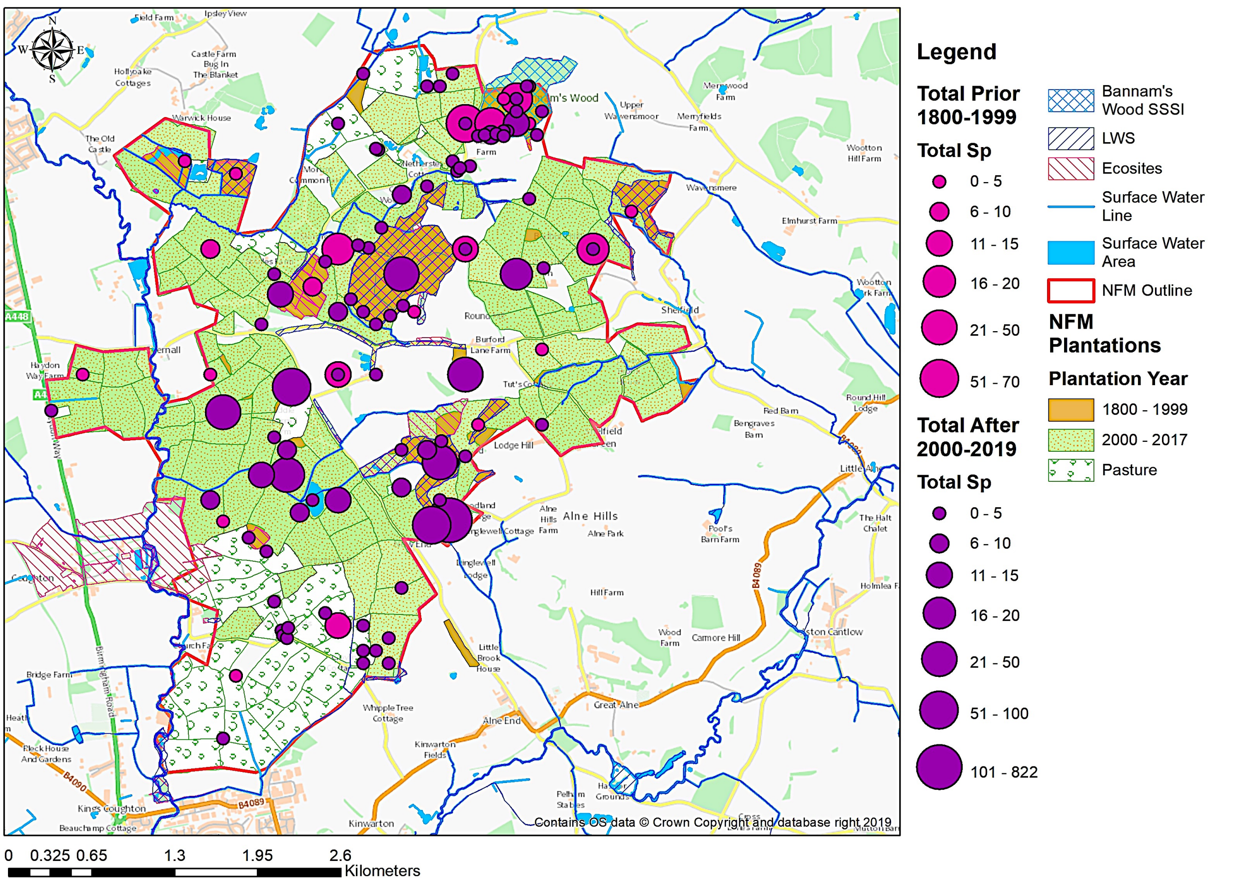

Figure 4.2 (a): Total population/number of individuals at each grid reference over time.

Species Presence in the Arrow Catchment Over Time

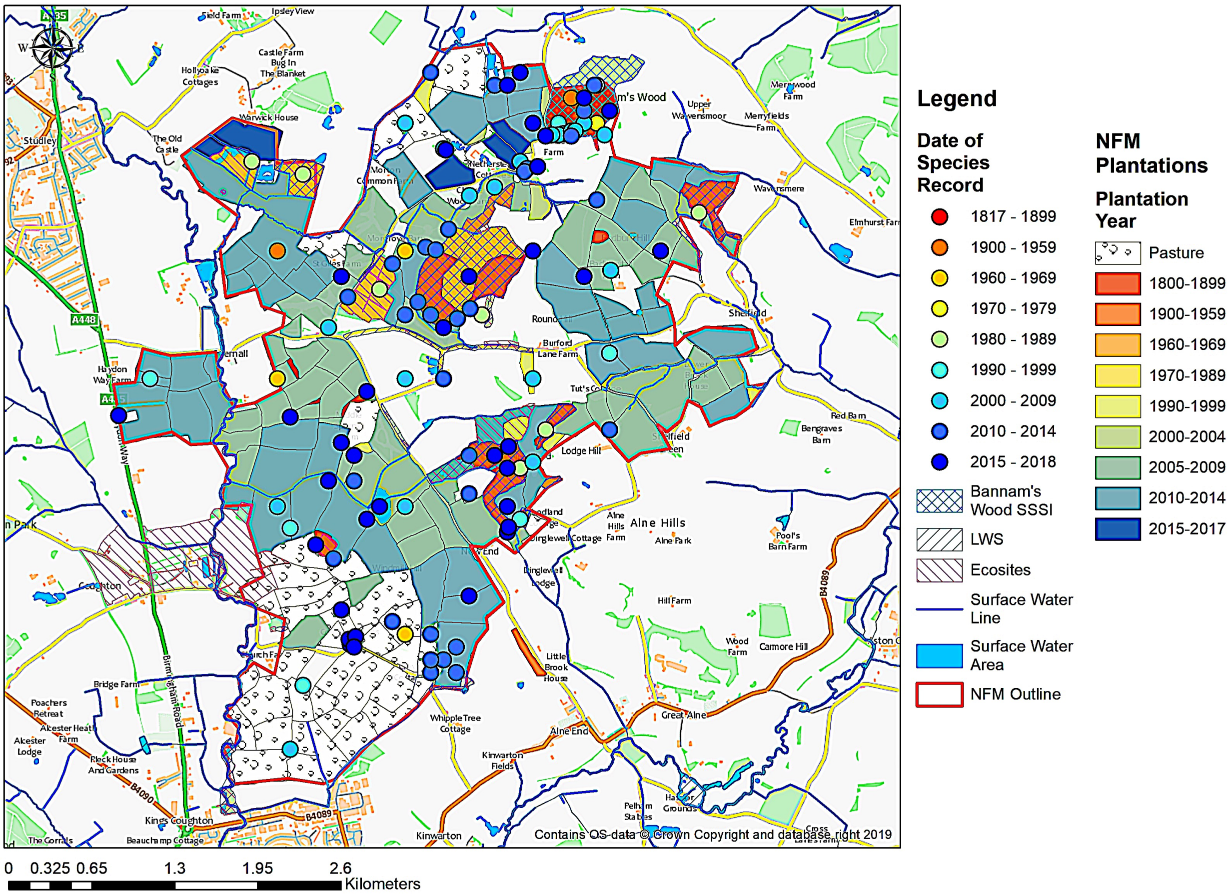

Figure 4.2 (b): Summative map of species presence and plantation date over time.

Figures 4.1 (a) and (b) and Figures 4.2 (a) and (b) demonstrate a large increase in faunal presence over time, after the implementation of the plantations. Between 1800-1999, species composition in the catchment was dominated by moderate populations of rare/notable floral species and invertebrates predominantly located within ASNW and ARW, with occasional records of mammals and amphibians (GCN) and invasive flora/fauna. In contrast, between 2000-2019 species composition was dominated by invertebrates and other fauna with minimal records of flora. Although some populations remain within the ASNW/ARW, large populations were also present across the NFM plantations and were predominantly recorded from 2010-2019 after the implementation of large areas of plantation across the catchment, with the largest cluster of records located adjacent to the drainage channel and ponds in Middle Spernal. This demonstrates the new plantations provide a suitable habitat for foraging, commuting and refugia for a wide range of fauna such as bats, amphibians, mammals and birds. This is supported by the mammal pathways, prints and sightings noted during site visits. The most notable increase in species are the two large populations of bats located in the south-east of the site. As demonstrated by the records and figures above, the two populations were recorded in 2015-2017 and comprised one roost of >800 Common Pipistrelle (*Pipistrellus pipistrellus)* and Soprano Pipistrelle (*Pipistrellus pygmaeus)* individuals recorded over two years and one roost 96 Common Pipistrelle individuals in 2015. This is a key population as bats are rare and highly protected by the Wildlife and Countryside Act (WCA) (1981) and the European Habitats and Species Directive (92/43/EEC) (1992). A range of other rare and protected fauna were also recorded across the catchment (refer to Appendix C for summary of species records).

4.2.2. Great Crested Newt Habitat Suitability Index (HSI) Assessment

The HSI assessment and suitability scores calculated for P1 and P2 are displayed within Tables 4.1 and 4.2 respectively. Scores range from 0.01 (unsuitable) – 1.0 (optimal).

Table 4.1: HSI Assessment of Pond 1.

Pond 1 (P1) – Environment Agency Pond			
Indices Number	**Habitat Suitability Factors**	**Result**	**Score**
1	Geographic location	A – Optimal	1.0
2	Pond area (m^2)	5,500 m^2	OMITTED
3	Permanence	Rarely Dries (No more than twice in 10 years)	1.0
4	Water quality (invertebrate scores)	Moderate (refer to 4.2.4)	0.67
5	Perimeter shade (%)	20%	1.0
6	Waterfowl presence	Minor	0.67
7	Fish presence	Absent	1.0
8	No of connected ponds within 1 km	5	0.71
9	Terrestrial habitat	Good (more than 75 %)	1.0
10	Macrophyte cover excluding duckweed (%)	20 %	0.5
HSI Score			**0.83**
Suitability			**Excellent**

As demonstrated by Table 4.1, P1 is classified as 'Excellent' suitability for GCN. This pond is situated in an optimal location within England and is surrounded by suitable terrestrial habitat likely to provide optimal opportunities for emerging newts. Terrestrial habitat is well structured semi-natural land with nearby hedges and ditches for foraging and shelter. The pond is of excellent suitability for breeding as it is unshaded, rarely dries, contains water of a moderate quality (moderate invertebrate community), a suitable substrate and areas for both open courtship and cover. Predation is unlikely to occur as fish are absent and waterfowl presence is minimal. P1 is also connected to 5 ponds within commuting distance. Furthermore, breeding amphibian and GCN presence in P1 was confirmed via researcher observation and surveys completed by the HofE Forest in 2020 respectively.

Table 4.2: HSI Assessment of Pond 2

Pond 2 (P2)– Scrape by HofE Forest			
Indices Number	**Habitat Suitability Factors**	**Result**	**Score**
1	Geographic location	Zone A – Optimal	1.0
2	Pond area (m^2)	15,000 m^2	OMITTED
3	Permanence	Rarely Dries (No more than twice in 10 years)	1.0
4	Water quality (invertebrate scores)	Moderate (refer to 4.2.4)	0.67
5	Perimeter shade (%)	10%	1.0
6	Waterfowl presence	Major	0.01
7	Fish presence	Absent	1.0
8	No of connected ponds within 1km	5	0.71
9	Terrestrial habitat	Good (more than 75%)	1.0
10	Macrophyte cover excluding duckweed (%)	10%	0.35
HSI Score			**0.74**
Suitability			**Good**

As demonstrated by Table 4.2, P2 is classified as ‘Good’ suitability for GCN. P2 is situated in an optimal location in England and is surrounded by suitable structured semi-natural terrestrial habitat. The pond is of good suitability for amphibian breeding as it rarely dries, is unshaded and contains water of moderate quality with no fish presence. Breeding amphibians were also observed within P2 in 2019. However, P2 is less suitable than P1, as it contained little macrophyte cover and waterfowl presence is major, with turbid water and a high concentration of suspended sediments. Furthermore, although emitted from the calculation, newt presence is less likely in a pond of 15,000m^2 in size.

4.2.3. Botanical Diversity and Evenness

The H’ and J’ values calculated for the River Arrow banks, NFM drainage channel and ponds with Eq. (2), Eq. (3) and Eq. (4) are outlined in Table 4.3.

Table 4.3: H’ and J’ scores of bankside flora of the River Arrow, NFM drainage channel and ponds.

Site	Species Richness	H’	J’	Total sp	Average H’	Average J’
River Arrow Banks						
ST	13	2.17	0.85	**62**	**1.81**	**0.80**
WTW	10	1.67	0.73			
NFM DP	6	1.15	0.64			
CC	8	1.63	0.78			
FD	6	1.55	0.86			
KC	19	2.68	0.91			
Drainage Channel Banks						
ED	10	1.65	0.72	**29**	**1.69**	**0.75**
CD	12	1.99	0.80			
WD	7	1.42	0.73			
Pond Banks						
P1	10	1.46	0.64	**23**	**1.85**	**0.76**
P2	13	2.23	0.87			
Scores were based on 3 quadrat assessments at each site. Please refer to Appendix D for full species lists.						

As shown by Table 4.3, the diversity and evenness scores of the River Arrow banks calculated between 1.15 and 2.68 (H’) and 0.64 and 0.91 (J’), suggesting a relatively diverse and evenly distributed floral community. Of the sites along the River Arrow, ST and KC contained the highest diversity scores and the largest number of species. This is reflected in the diversity and evenness scores of the NFM drainage channel, which calculated between 1.42 and 1.99 (H’) and 0.72 and 0.80 (J’). The species identified along the main channel were those typical to open grassland and hedgerows rather than woodland as the surrounding woodland plantations were all aged between 10 and 12 years. However, as the woodlands mature, this is likely to change.

Furthermore, the diversity and evenness scores of P1 and P2, which calculated between 1.46 and 2.23 (H’) and 0.64 and 0.87 also suggest that the NFM contained a relatively diverse and evenly distributed floral community. Both ponds were surrounded by dense naturally colonised terrestrial vegetation typical to pond edges. The mix of dense vegetation surrounding the ponds and main channel are likely to both slow runoff infiltration and provide opportunities for both floral and faunal species. This was evidenced through the observed mammal tracks and sightings of wildlife seen throughout the NFM site.

4.2.4. Macroinvertebrate Communities

The NTAXA EQR and ASPT EQR calculated with the WHPT method in RICT and the H' and J' values calculated with Eq. (2), Eq. (3) and Eq. (4) are outlined in Table 4.4 (a) and (b).

Table 4.4 (a): Macroinvertebrate variation across the catchment – individual sites.

Site	NTAXA EQR	NTAXA Status	ASPT EQR	ASPT Status	H'	J'
River Arrow						
ST	0.47	P/B	0.86	M/G	2.2	0.9
WTW	0.41	B	0.74	M	1.8	0.8
NFM DP	0.47	P/B	0.87	G	1.7	0.7
CC	0.43	B	0.81	M	1.8	0.8
FD**	0.39	/	0.78	/	1.7	0.8
KC	0.58	M	0.88	G	2.0	0.8
Drainage Channel						
ED	0.2	B	0.82	M	0.5	0.4
CD	0.18	B	0.88	G	0.4	0.4
WD	0.49	P	1.03	H	1.4	0.6
Ponds						
P1	0.37	B	0.77	M	1.5	0.7
P2	0.31	B	0.81	M	1.5	0.8
**: Based on data from the summer season only. WFD status could not be calculated with a single season. Refer to Appendix E for full survey results.						

Table 4.4 (b): Macroinvertebrate variation across the catchment.

Waterbody	Average EQR		6-Month Status		Average H'	Average J'
	NTAXA	ASPT	NTAXA	ASPT		
River Arrow	0.48	0.84	P	G	1.86	0.80
Drainage Channel	0.29	0.92	B	G	0.78	0.47
Pond	0.35	0.79	B	G	1.51	0.79

As demonstrated by Tables 4.4 (a) and (b), the EQR values for NTAXA are significantly lower than the ASPT values. All sites apart from KC ('Moderate') were classified as 'Bad' or 'Poor' status for WFD-UKTAG/WFD scoring for NTAXA. However, in contradiction, the ASPT values calculated for the Arrow catchment ranged from 'Moderate'- 'Good' status in the River Arrow, 'Moderate'- 'High' in the main drainage channel and 'Moderate' in the ponds. A clear increase in ASPT was observed as the drainage channel flowed west, demonstrating a clear increase in water quality to the point of outfall. H' and J' scores also demonstrate reasonably diverse and even populations in the main river and ponds but is much lower for the drainage channel. However, WD was higher in diversity than ED and CD.

Significant differences Between Sites

Tables 4.5 (a) and (b) outline significant differences between sites.

Table 4.5 (a): Kruskal-Wallis/Mann-Whitney-U (ponds) results (MI) – within waterbodies.

Location	NTAXA P-Value	ASPT P-Value
River Arrow	0.359	0.264
Drainage Channel	0.180	0.156
Ponds	0.667	1.000

Table 4.5 (b): Kruskal-Wallis results (MI) – between waterbodies.

Location	NTAXA P-Value	ASPT P-Value
Overall Catchment	0.038*	0.132
Post-Hoc Multiple Comparisons		
River Arrow and Drainage Channel	0.044*	-
River Arrow and Ponds	0.390	-
Drainage Channel and Ponds	1.000	-

Tables 4.5 (b) indicates NTAXA was significantly higher in the river compared to the drainage channel, most likely due to size. No other significant differences were identified between individual sites for NTAXA (p=0.130) or ASPT (p=0.346) or between seasons for NTAXA (p=1.000) or ASPT (p=1.000).

Temporal Variation

Table 4.6: 2019 spring/autumn EQR, status and official historical catchment status classifications.

<table>
<tr><th rowspan="2">Waterbody</th><th colspan="2">Average EQR</th><th colspan="2">6-Month Status</th><th colspan="5" rowspan="2">Past EA Catchment Status macroinvertebrates – Arrow*</th></tr>
<tr><th>NTAXA</th><th>ASPT</th><th>NTAXA</th><th>ASPT</th></tr>
<tr><td>River Arrow</td><td>0.48</td><td>0.84</td><td>P</td><td>G</td><td rowspan="3">M
2009</td><td rowspan="3">P
2010</td><td rowspan="3">G
2011</td><td rowspan="3">M
2013</td><td rowspan="3">G
2014-
2016</td></tr>
<tr><td>Main NFM Drainage Channel</td><td>0.29</td><td>0.92</td><td>B</td><td>G</td></tr>
<tr><td>Pond</td><td>0.35</td><td>0.79</td><td>B</td><td>G</td></tr>
<tr><td colspan="10">*Official EA catchment status classifications only include the main River Arrow and its tributaries. No data recorded for 2012</td></tr>
</table>

As demonstrated by Table 4.6, quality scores have been in fluctuation for several years. Although, in recent years a general increase in quality scoring has been observed. This is supported by the ‘Good’ quality ASPT scores. However, NTAXA scores indicate limited populations and a ‘Poor’ or ‘Bad’ quality.

4.3. Physico-Chemical Indicators

The section below explores 9 physico-chemical indicators of water quality across the Arrow catchment and (if possible) classifies the quality status in accordance with the methods and status classifications as outlined by the UK Technical Advisory Group (WFD-UKTAG) under the WFD (2000/60/EC). Standards are displayed on graphs as lines. Refer to Appendix F for monthly graph values for physico-chemical indicators.

4.3.1. Acid Conditions - pH

Figure 4.3 and Tables 4.7 (a) and (b) outline a summary of the pH across the catchment and the status of each site and waterbody based on 6-months of data.

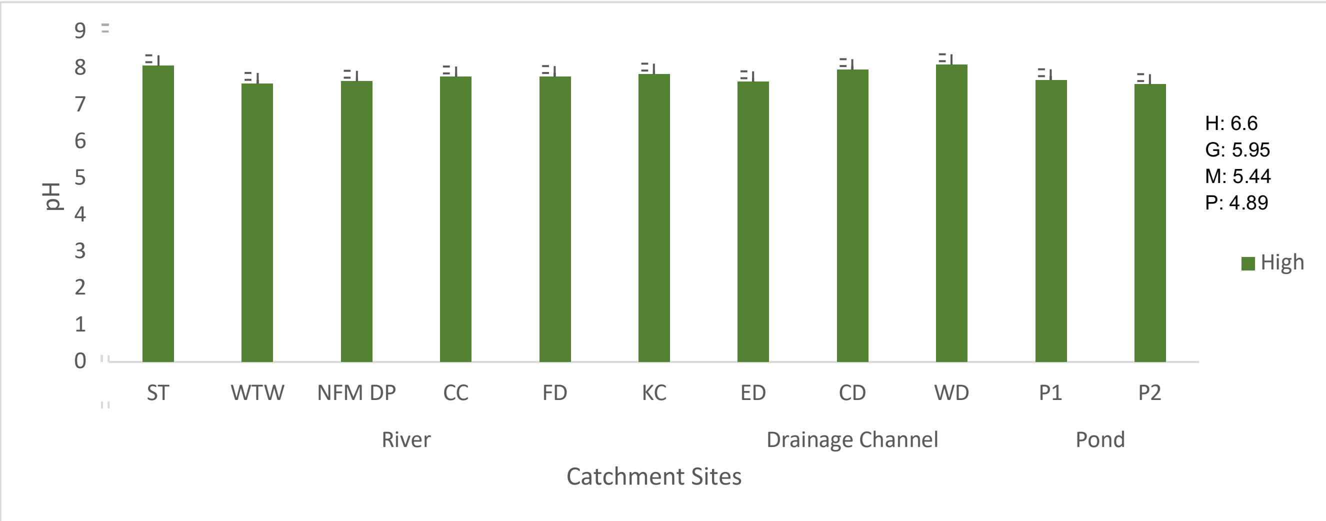

Figure 4.3: Average pH of the Arrow catchment over 6 months and status according to WFD-UKTAG standards (+/- 1 SE).

Table 4.7 (a): 6-month summary of the variation in pH across individual sites.

Test	ST	WTW	NFM DP	CC	FD	KC	ED	CD	WD	P1	P2
Mean	8.1	7.6	7.6	7.8	7.8	7.8	7.6	8.0	8.1	7.7	7.6
SD	0.33	0.46	0.40	0.41	0.43	0.27	0.44	0.32	0.20	0.30	0.32
Status	H	H	H	H	H	H	H	H	H	H	H
Seasonal Variation – Mann-Whitney U											
Spring	8.0	7.5	7.5	7.6	7.7	7.8	7.5	7.9	8.0	7.8	7.5
Summer	8.1	7.7	7.8	7.9	7.9	7.9	7.7	8.0	8.2	7.6	7.6
P-Value	1.000	0.818	0.343	0.818	0.762	0.429	0.329	0.699	0.310	0.132	1.000

Table 4.7 (b): 6-month summary of the variation in pH across the catchment.

Test	River Arrow	Drainage Channel	Ponds
Mean	7.8	7.9	7.6
SD	0.41	0.38	0.31
Status	H	H	H

As demonstrated by the data in Figure 4.3 and Tables 4.7 (a) and (b), the acid conditions of the Arrow catchment remained stable between pH 7 and 8 with little variation throughout the 6 months of observations, therefore indicating a high quality. Although slight acidification most likely due to influx of contaminants from stormwater runoff was observed in May, it had no detrimental impact to quality. Furthermore, there was no significant difference in pH between spring and summer.

<u>Significant Differences Between Sites</u>

Tables 4.8 (a-c) below outline the variation detected across the catchment.

Table 4.8 (a): Kruskal-Wallis/Mann-Whitney-U (ponds) results (pH) – within waterbodies.

Location	**P-Value**
River Arrow	0.021*
Drainage Channel	0.013*
Ponds	0.205

Table 4.8 (b): Kruskal-Wallis results (pH) – between waterbodies.

Location		**P-Value**
Overall Catchment		0.007**
Post-Hoc Multiple Comparisons		
River Arrow	Drainage Channel	0.073
	Ponds	0.445
Drainage Channel	Ponds	0.005**

Table 4.8 (c): Kruskal-Wallis significant results (pH) – individual sample sites.

Location		**P-Value**
Overall Catchment		<0.001***
Post-Hoc Multiple Comparisons		
ST	WTW	0.016*
	NFM DP	0.039*
	P2	0.013*
WD	ED	0.046*
	WTW	0.024*
	P2	0.002**

As demonstrated by Tables 4.8 (a-c), a significant difference between the drainage channel and ponds (p=<0.005**) was identified. A significant variance was found in the river (p=0.021*), comprising significant differences between ST and WTW (p=0.016*) and ST and NFM DP (p=0.039*). pH in the drainage channel also varied significantly (p=0.015*), with differences between ED and WD (p=0.046*). Across the catchment, a significant difference between WD and WTW (p=0.024*) and WD and P2 (p=0.002**) was also identified as WTW and P2 were significantly lower in pH.

Temporal Variation

Table 4.9: 2019 6-month pH status and official historical catchment status classifications.

Waterbody	6-Month Status	Past EA Catchment Status Classifications for pH – Arrow*
River Arrow	High	High (Cycles 1&2)
Main NFM Drainage Channel	High	
Ponds	High	
*Official EA catchment status classifications only includes the main River Arrow and its tributaries		

As outlined in Table 4.9, the Arrow catchment has been consistently classified as 'High' quality for pH since 2009 and remains as such in 2019, as the region is generally more alkaline. It is therefore likely that the pH remained stable for the remainder of the hydrological year and passed as 'High' quality.

4.3.2. *Temperature (ºC)*

As only a limited number of differences have been identified and temperature is not currently an issue in the Arrow catchment, the supporting data is provided in Appendix G. A summary of the temperature over a 6-month period is provided below and is displayed in Figure 4.4.

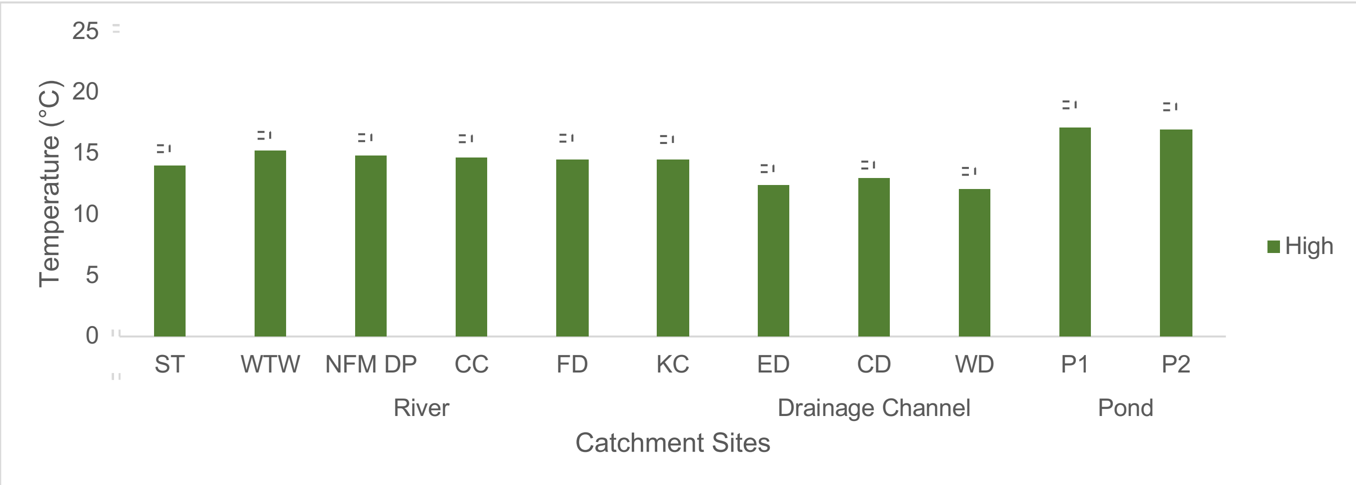

Figure 4.4: Average Temperature (ºC) of the Arrow catchment over 6 months and status according to WFD-UKTAG standards (+/- 1 SE).

Temperature averaged at c.10-12°C in the River Arrow in the spring with a gradual increase to c. 16-18°C in summer. The main drainage channel was consistently c. 1-2°C cooler than the River Arrow at c. 9-10°C in spring and c.15°C in summer ($p=0.045^*$). The ponds averaged at the highest temperature of c.12-13°C (spring) and c. 21°C (summer) and were significantly different to the drainage channel ($p=<0.001^{***}$). No other significant differences were found between sites ($p=0.078$). However, for seasonal change, summer was significantly warmer in all cases as is to typically be expected. As temperature is a 98-percentile standard, no samples can exceed the standard threshold more than 2% of the time to achieve the status. No sites exceeded 25°C at any point, including at the warmest point of the summer, therefore, the catchment is classified as 'High'. The Arrow catchment has also been classified as 'High' quality for temperature for both Cycles 1 and 2.

4.3.3. Dissolved Oxygen (DO)

The DO levels of the Arrow catchment are outlined in Figures 4.5 (a-c).

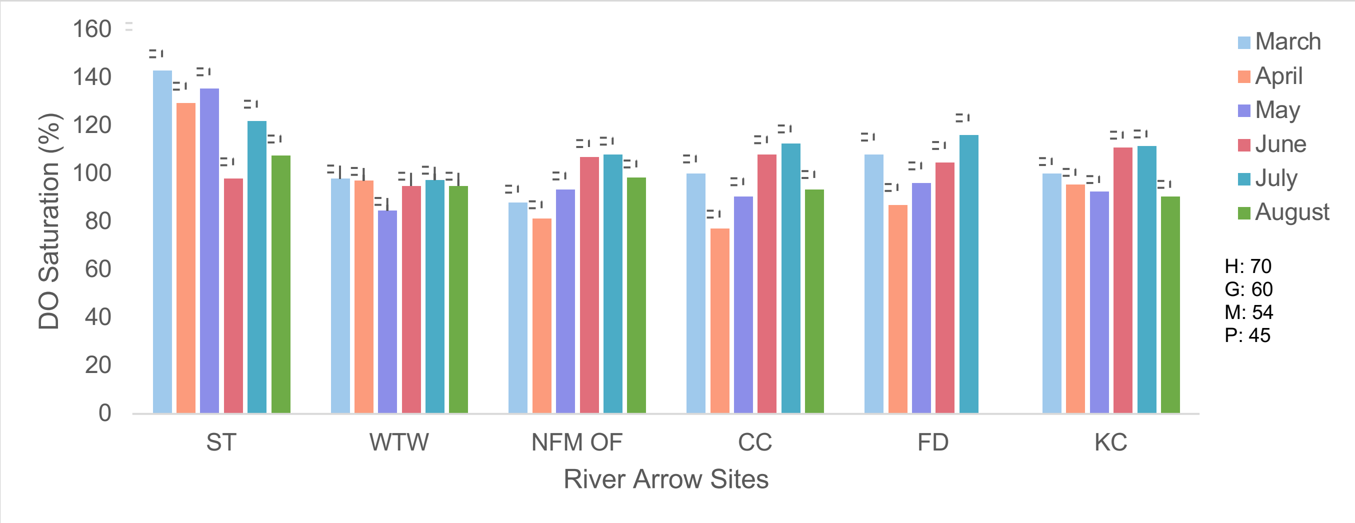

Figure 4.5 (a): Average monthly DO (% saturation) of the River Arrow over 6 months (+/- 1 SE).

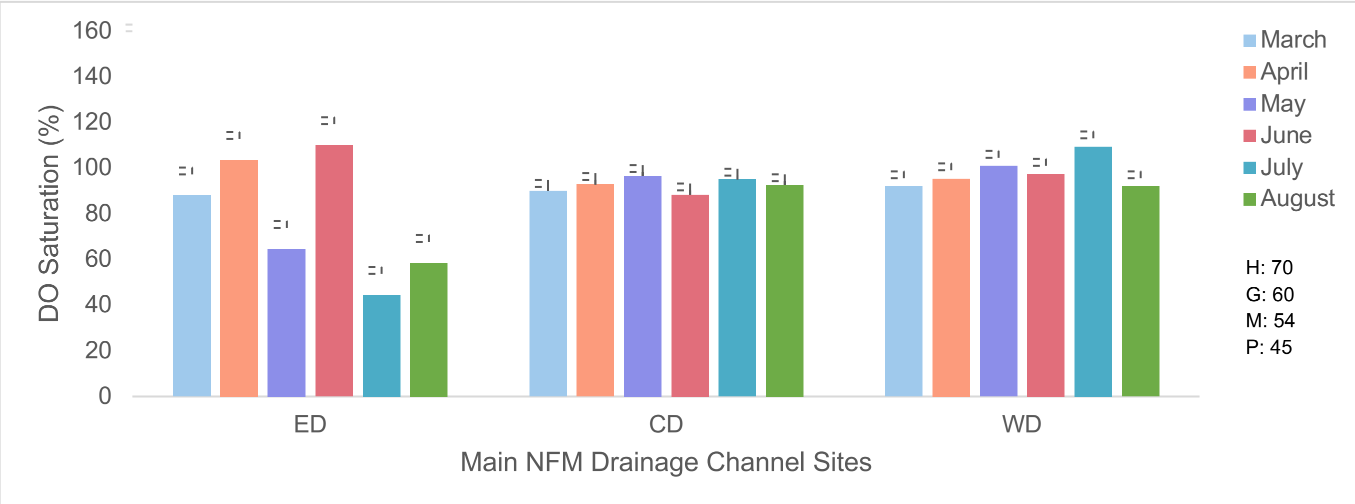

Figure 4.5 (b): Average monthly DO (% saturation) of the main NFM drainage channel over 6 months (+/- 1 SE).

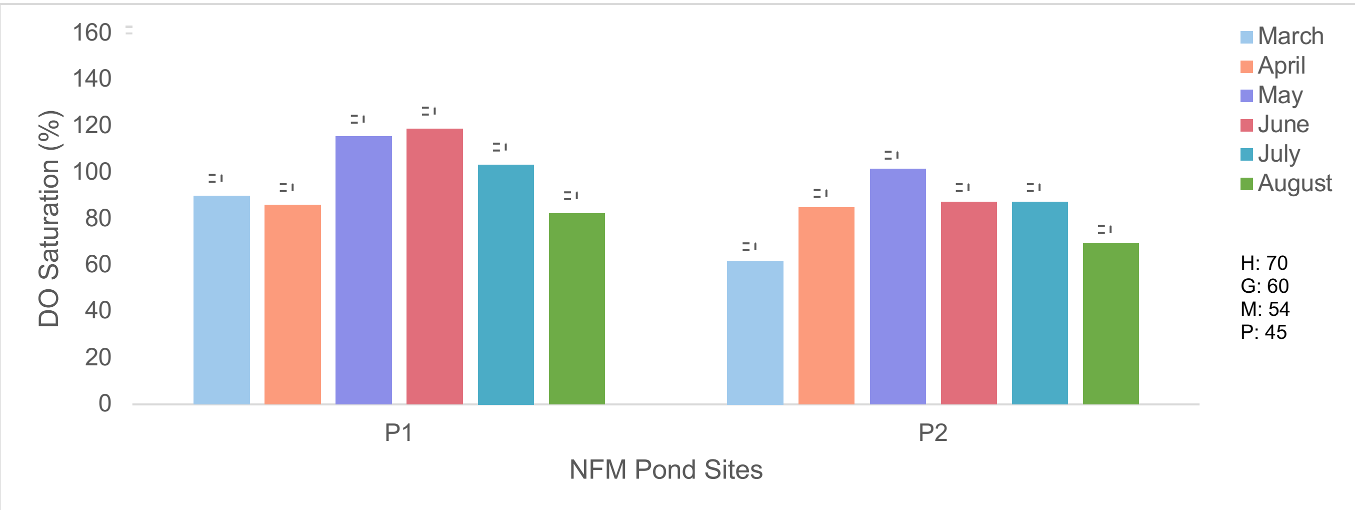

Figure 4.5 (c): Average monthly DO (% saturation) in the River Arrow over 6 months (+/- 1 SE).

As demonstrated by Figure 4.5 (a), the oxygen within the River Arrow fluctuated between 75-140% saturation and did not fall below 70%, indicating high quality and plentiful available oxygen. Although, a slight decrease in O_2 was consistently observed from ST to WTW, it was not detrimental to the quality or significant (p=1.000). However, Figure 4.5 (b) indicates the drainage channel fluctuated much more. In the shallow, slow-flowing eastern extent (ED) the O_2 fluctuated between 60-100% in spring and 45-100% in summer. After the first attenuation in the east, the drainage channel flowed as a larger stream with a high quality of 90-110% saturation. Finally, as demonstrated by Figure 4.5 (c), the DO of P1 fluctuated between 80-100%, where P2 contained slightly less O_2 between 60-100%, rising from good quality in March to high. Both ponds observed a peak in May-June and slowly declined.

<u>Significant differences Between Sites</u>

Tables 4.10 (a-c) outline significant differences between sites.

Table 4.10 (a): Kruskal-Wallis/Mann-Whitney-U (ponds) results (DO) – within waterbodies.

Location	**P-Value**
River Arrow	0.022*
Drainage Channel	0.340
Ponds	0.139

Table 4.10 (b): Kruskal-Wallis results (DO) – between waterbodies.

Location		**P-Value**
Overall Catchment		0.024*
Post-Hoc Multiple Comparisons		
River Arrow	Drainage Channel	1.000
	Ponds	0.123
Drainage Channel	Ponds	0.058

Table 4.10 (c): Kruskal-Wallis significant results (DO) – individual sample sites.

Location		**P-Value**
Overall Catchment		0.001***
Post-Hoc Multiple Comparisons		
ST	WTW	0.020*
	P2	0.002**
	ED	0.004**

As demonstrated by Tables 4.10 (a-c) a significant difference within the River Arrow was noted (ST and NFM DP) (p=0.028*). Significant differences between ST and P2 (<0.001***) and ST and ED (p=0.004**) were also identified, in which ST was significantly higher in % saturation. No other significant differences were noted within the catchment.

Spatial and Seasonal Variation Across the Catchment

Figure 4.6 and Tables 4.11 (a) and (b) below outline a summary of variation across the catchment.

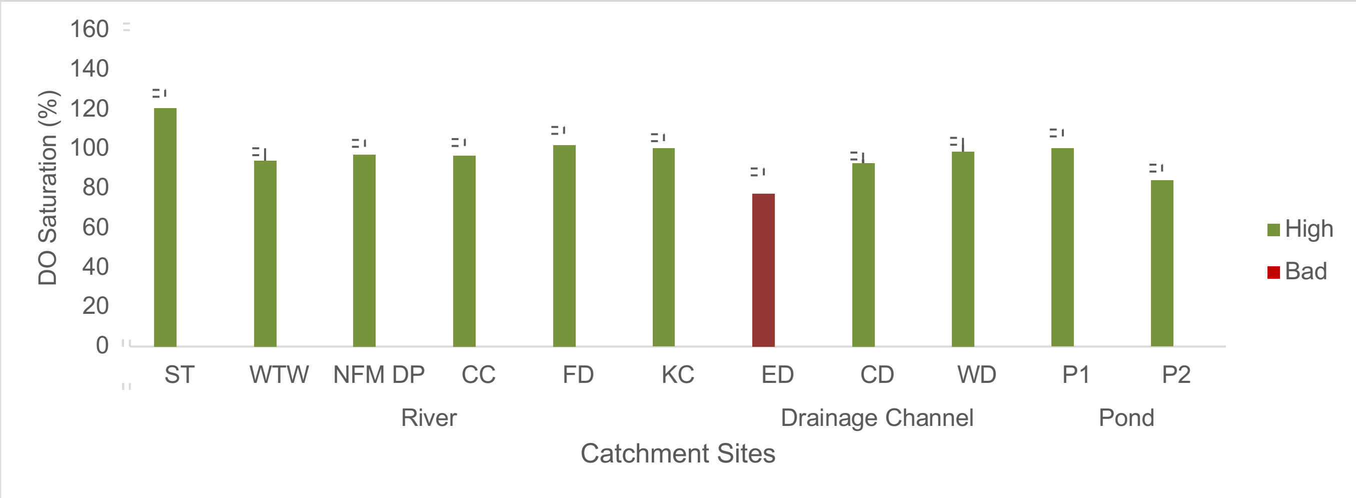

Figure 4.6: Average DO (% saturation) of the Arrow catchment over 6 months and status classification according to WFD-UKTAG standards for each individual site (+/- 1 SE).

Table 4.11 (a): 6-month summary of the variation in DO across individual sites.

Test	**ST**	**WTW**	**NFM DP**	**CC**	**FD**	**KC**	**ED**	**CD**	**WD**	**P1**	**P2**
Mean (%)	121	94	97	97	102	100	77	93	98	100	84
SD	18.48	8.76	14.19	17.01	17.84	12.57	30.94	6.13	12.23	20.15	1.53
Status	H	H	H	H	H	H	B	H	H	H	H
Seasonal Variation – Mann-Whitney U											
Spring	135	92	88	87	95	95	85	94	97	99	87
Summer	109	96	105	105	110	104	71	92	100	102	82
P-Value	0.052	0.662	0.012*	0.247	0.286	0.247	0.792	0.931	1.000	1.000	0.082

Table 4.11 (b): 6-month summary of the variation in DO across the catchment.

Test	**River Arrow**	**Drainage Channel**	**Ponds**
Mean (%)	102	90	92
SD	17.086	20.982	19.323
Status	H	M	H

As demonstrated by Tables 4.11 (a) and (b), although ED averaged at 77%, the % saturation recorded was below the standard for poor more than 10% of the time (18%). Therefore, the high standard is failed, and 'Bad' status given for ED. However, the main drainage channel classified as 'Moderate', as the standard was not failed more than 10% of the time over the waterbody as a unit. The remainder of the sites did not fall below 70% at any time and therefore classify as 'High'. It was also found that the summer average of NFM DP was significantly higher than spring (p=0.012*). Although % saturation was slightly higher in summer for most other sites, none significantly varied.

Temporal Variation

Table 4.12: 2019 6-month DO status and official historical catchment status classifications.

Waterbody	6-Month Status	Past EA Catchment Status Classifications for DO – Arrow*
River Arrow	High	High (Cycles 1&2)
Main NFM Drainage Channel	Moderate	
Pond	High	
*Official EA catchment status classifications only include the main River Arrow and its tributaries.		

As demonstrated by Table 4.12, the river catchment has been classified as ‘High’ since 2009 and remains as such in 2019. As both the river and ponds were classified as high, these waterbodies are therefore likely to support an abundant aquatic community. Furthermore, although the drainage channel was not on par with the river due to the bad status of ED, it improved to ‘High’ quality at the point of discharge into the river (WD). The NFM has therefore caused no negative or significantly positive impact in terms of classification for this indicator.

4.3.4. Biochemical Oxygen Demand (BOD_5)

The BOD_5 values calculated for the River Arrow are outlined in Figures 4.7 (a-c).

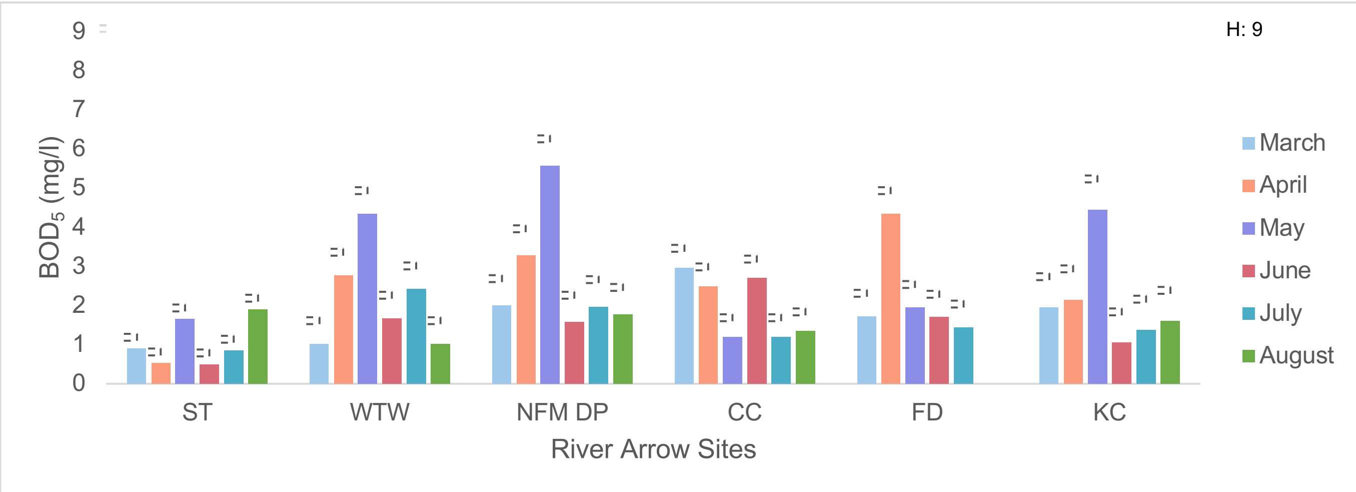

Figure 4.7 (a): Average monthly BOD_5 (mg/l) of the River Arrow over 6 months (+/- 1 SE).

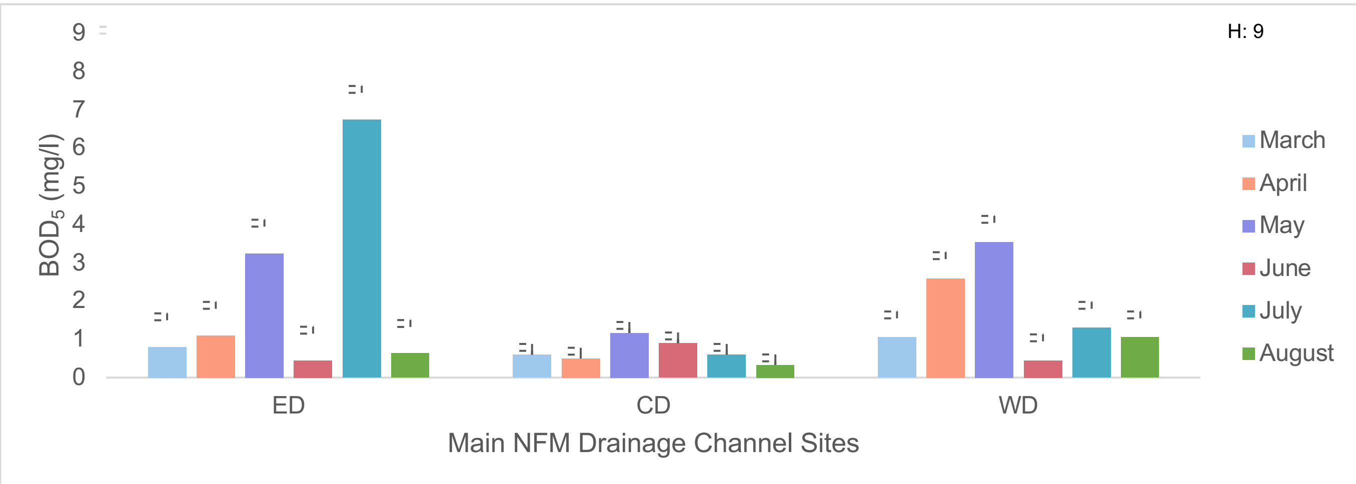

Figure 4.7 (b): Average monthly BOD_5 (mg/l) of the main NFM drainage channel over 6 months (+/- 1 SE).

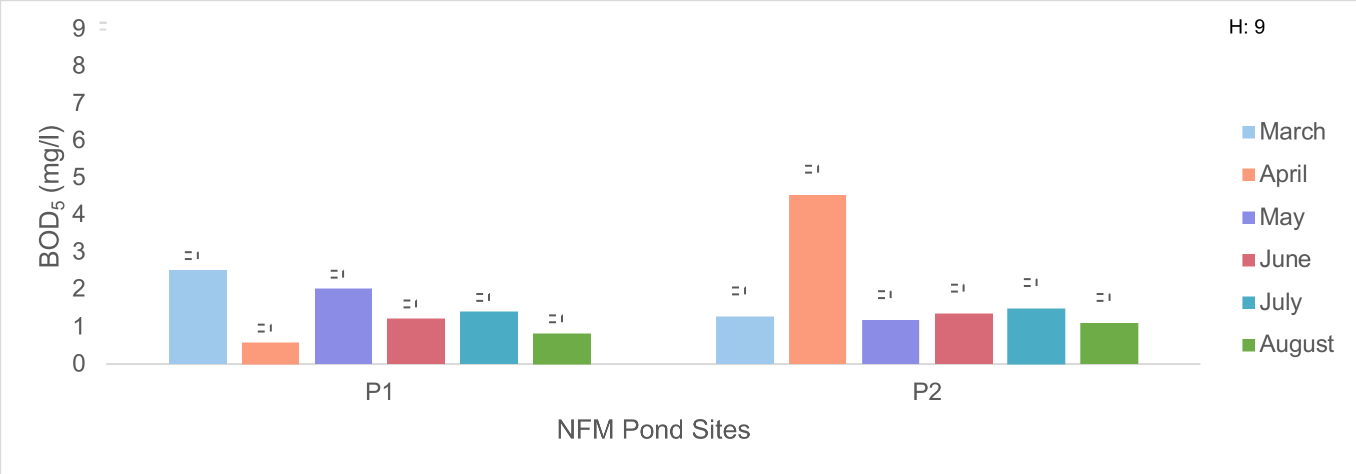

Figure 4.7 (c): Average monthly BOD$_5$ (mg/l) of the NFM ponds over 6 months (+/- 1 SE).

As demonstrated by Figure 4.7 (a) (b) and (c), BOD$_5$ across the catchment varied between 0.5 and 5.5mg/l indicating all sites were of a high quality with plentiful oxygen. A notable increase in BOD$_5$ was observed across the catchment in April and May due to the occurrence of storm activity and an influx of contaminants. In the River Arrow, an increase from ST to the WTW was found but was not statistically significant (p=1.000) and no apparent trend was observed across the river. However, a general decline in BOD$_5$ was observed in the drainage channel as it flowed west as BOD$_5$ was at its highest in ED (c. 1-6mg/l) and fell to c. 1mg/l in CD and WD. However, some fluctuations from the trend were observed such as large peak in ED in July which was not observed at any other point. The BOD$_5$ of P1 declined over time from 2-1mg/l and P2 remained relatively stable at 1mg/l with a peak likely caused by stormwater.

Significant Differences Between Sites

Tables 4.13 (a-c) outline significant differences between sites.

Table 4.13 (a): Kruskal-Wallis/Mann-Whitney-U (ponds) results (BOD$_5$) – within waterbodies.

Location	P-Value
River Arrow	0.070
Drainage Channel	0.110
Ponds	0.603

Table 4.13 (b): Kruskal-Wallis results (BOD$_5$) – between waterbodies.

<table>
<tr><th colspan="2">Location</th><th>P-Value</th></tr>
<tr><td colspan="2">Overall Catchment</td><td>0.02*</td></tr>
<tr><td colspan="3">Post-Hoc Multiple Comparisons</td></tr>
<tr><td rowspan="2">River Arrow</td><td>Drainage Channel</td><td>0.015*</td></tr>
<tr><td>Ponds</td><td>0.444</td></tr>
<tr><td>Drainage Channel</td><td>Ponds</td><td>1.000</td></tr>
</table>

Table 4.13 (c): Kruskal-Wallis significant results (BOD_5) – individual sample sites.

Location		**P-Value**
Overall Catchment		<0.001***
Post-Hoc Multiple Comparisons		
CD	NFM DP	0.005**

As demonstrated by Tables 4.13 (a-c), a significant difference between the River Arrow and drainage channel (p=0.015*) was observed, as BOD_5 in NFM DP was significantly higher than CD (p=0.005**). However, no significant differences were noted between the River Arrow sites suggesting no significant pollutants were discharged from the NFM and no significant impact was found. No other significant differences between sites across the catchment were observed.

<u>Spatial and Seasonal Variation Across the Catchment</u>

Figure 4.8 and Tables 4.14 (a) and (b) outline a summary of the BOD_5 across the catchment and the status of each site and waterbody based on 6-months of data.

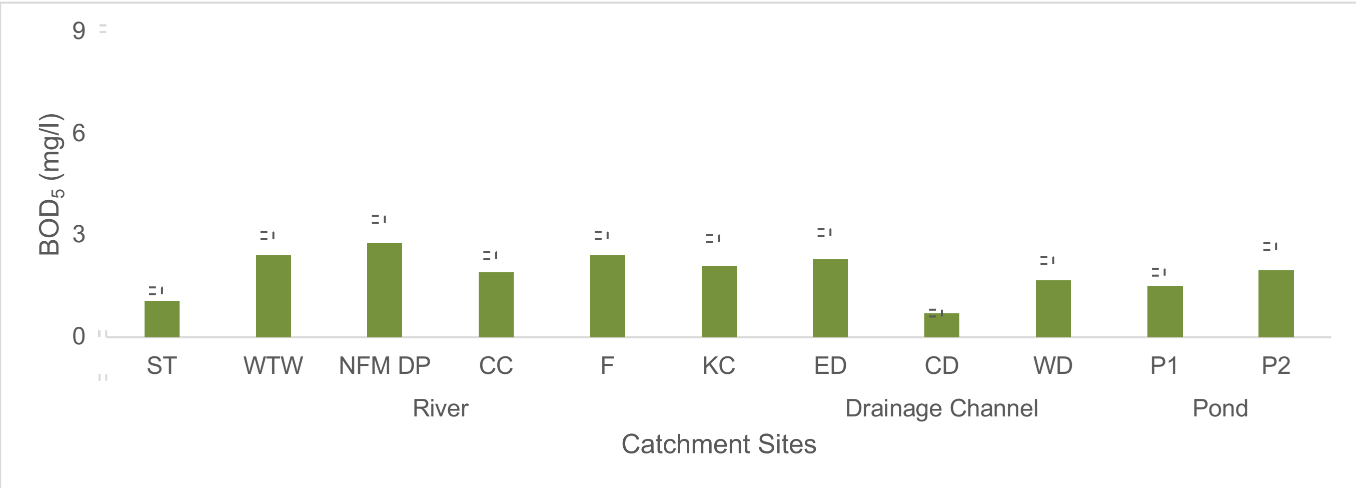

Figure 4.8: Average BOD_5 (mg/l) of the Arrow catchment over 6 months and status according to WFD-UKTAG standards (+/- 1 SE).

Table 4.14 (a): 6-month summary of the variation in BOD_5 across individual sites.

Test	**ST**	**WTW**	**NFM DP**	**CC**	**FD**	**KC**	**ED**	**CD**	**WD**	**P1**	**P2**
Mean	1.1	2.4	2.8	1.9	2.4	2.1	2.3	0.7	1.7	1.5	2.0
SD	0.98	1.78	2.04	1.25	1.67	2.34	2.64	0.47	1.63	1.26	2.05
Status	H	H	H	H	H	H	H	H	H	H	H
Seasonal Variation – Mann-Whitney U											
Spring	1.1	2.7	3.6	2.4	2.7	3.0	1.9	0.8	2.4	1.7	2.3
Summer	1.1	1.7	1.8	1.8	1.6	1.3	2.6	0.6	0.9	1.2	1.3
P-Value	0.662	0.589	0.106	0.537	0.476	0.662	0.931	0.485	0.132	0.699	0.810

Table 4.14 (b): 6-month summary of the variation in BOD_5 across the catchment.

Test	River Arrow	Drainage Channel	Ponds
Mean	2.1	1.5	1.6
SD	1.75	1.85	1.68
Status	H	H	H

As demonstrated by Tables 4.14 (a) and (b), in the 6 months of monitoring, none of the sites exceeded the 9mg/l threshold at any point and are therefore classified as 'High' quality for this indicator as BOD_5 is a 99-percentile standard (no samples can exceed 9mg/l more than 1% of the time). The standard deviation for each site was slight with NFM DP, KC, ED and P2 being the most varied, however, no significant difference between seasons was identified.

<u>Temporal Variation</u>

Table 4.15: 2019 6-month BOD_5 status and official historical catchment status classifications.

Waterbody	6-Month Classification	Past EA Catchment Status Classifications for BOD_5 – Arrow*	
River Arrow	High	Good (2012-2014)	High (2015-2016)
Main NFM Drainage Channel	High		
Pond	High		
*Official EA catchment status classifications only include the main River Arrow and its tributaries			

As demonstrated by Table 4.15, BOD_5 in the catchment has improved from 'Good' in 2012-2014 to 'High' in 2015-2016 and remains as such in 2019. It is also therefore likely the quality remained at the monitored level for the remainder of the hydrological year.

4.3.5. Total Reactive Phosphorus (TRP)

The TRP concentrations detected in the Arrow catchment are outlined in Figures 4.9 (a-c).

Figure 4.9 (a): Average monthly TRP (µg/l) in the River Arrow over 6 months (+/- 1 SE).

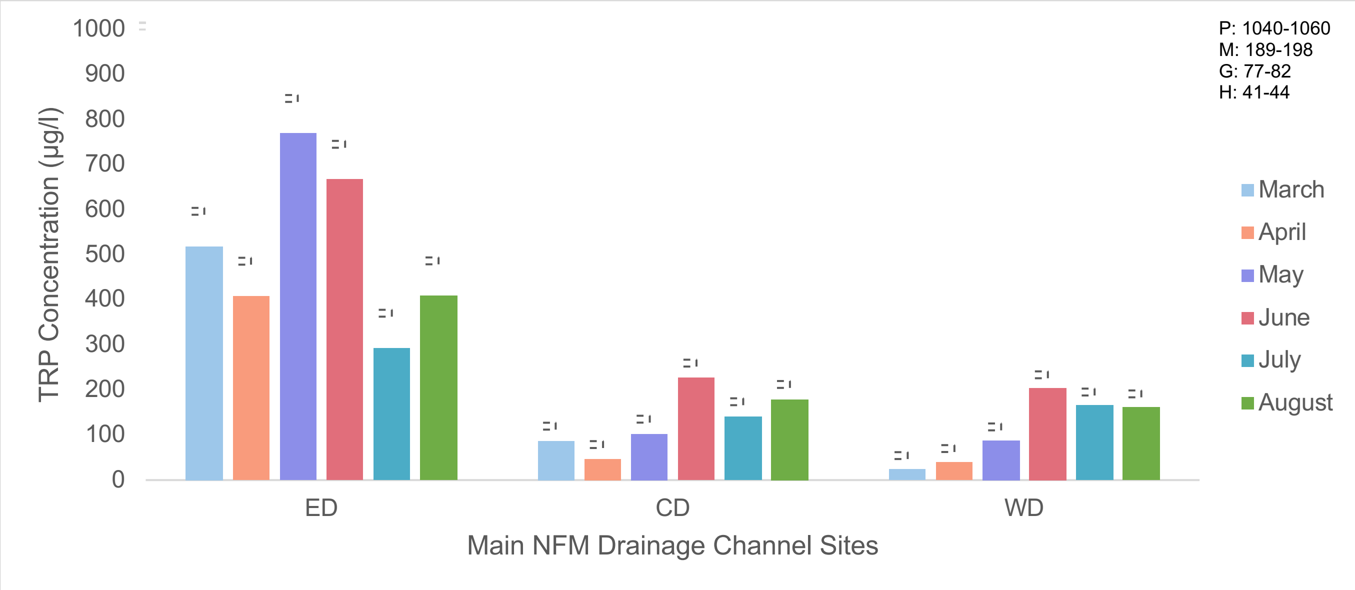

Figure 4.9 (b): Average monthly TRP (µg/l) in the main NFM Drainage channel over 6 months (+/- 1 SE).

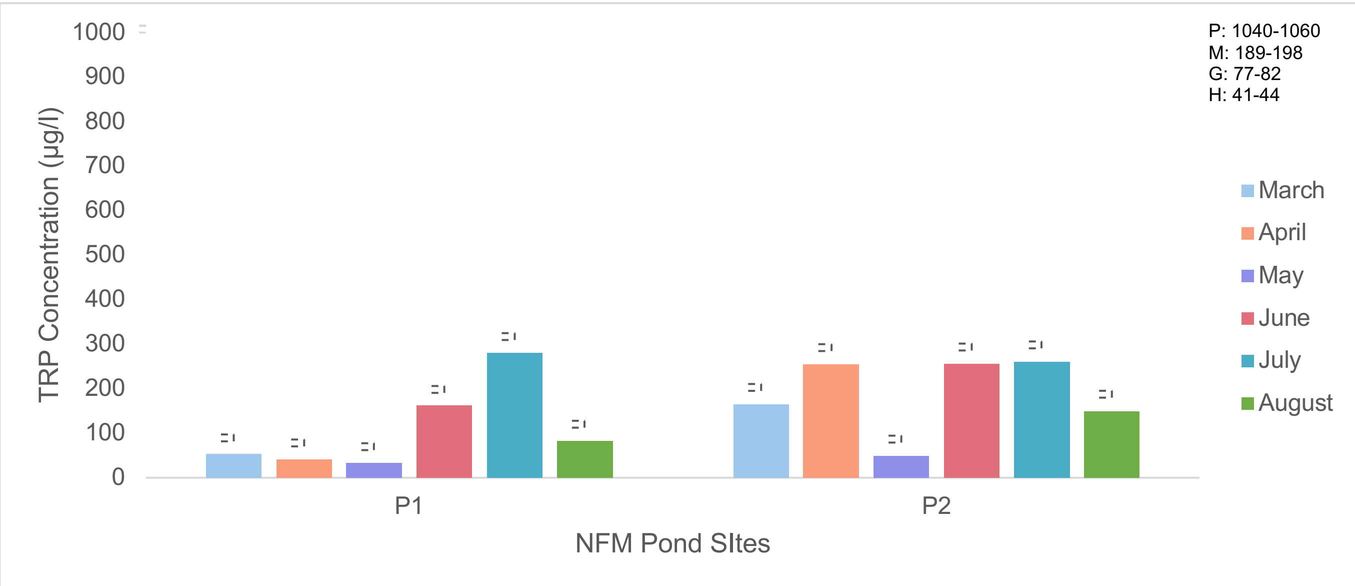

Figure 4.9 (c): Average monthly TRP (µg/l) in the NFM ponds over 6 months (+/- 1 SE).

Figure 4.9 (a) demonstrates that the River Arrow contained moderate concentrations of TRP, which fluctuated significantly over 6 months. Concentrations consistently increased from <400µg/l in ST to c. 500-800µg/l at the WTW and decreased downstream. TRP also increased after a series of storms in spring and declined rapidly in June. Figure 4.9 (b) demonstrates that TRP concentration in ED mirrored the fluctuation of the river (likely caused by stormwater) and contained unstable concentrations of TRP ranging from 130 – 1000µg/l, indicating moderate quality which degraded close to the threshold for poor. However, CD and WD were consistently significantly lower, ranging between 3-290µg/l indicating high - moderate quality. Low concentrations of TRP were also present in the ponds as demonstrated by Figure 4.9 (c), in which TRP ranged between 20-250µg/l indicating high-moderate quality.

Significant differences Between Sites

Tables 4.16 (a-c) outline significant differences between sites.

Table 4.16 (a): Kruskal-Wallis/Mann-Whitney-U (ponds) results (TRP) – within waterbodies.

Location	P-Value
River Arrow	0.001***
Drainage Channel	<0.001***
Ponds	0.065

Table 4.16 (b): Kruskal-Wallis results (TRP) – between waterbodies.

Location		P-Value
Overall Catchment		<0.001***
Post-Hoc Multiple Comparisons		
River Arrow	Drainage Channel	<0.001***
	Ponds	<0.001***
Drainage Channel	Ponds	0.569

Table 4.16 (c): Kruskal-Wallis significant results (TRP) – individual sample sites.

Location		P-Value
Overall Catchment		0.001***
Post-Hoc Multiple Comparisons		
P2	WTW	0.002**
	NFM DP	0.010**
ST	WTW	0.001***
	NFM DP	0.001***
ED	WD	<0.001***
	CD	0.002**
P1	WTW	<0.001***
	NFM DP	<0.001***
	CC	0.002**
	FD	0.012**
	KC	0.001***
	ED	0003**
WD	WTW	<0.001***
	NFM DP	<0.001***
	CC	0.002**
	FD	0.015**
	KC	0.001***
	ED	0003**
CD	WTW	<0.001***
	NFM DP	<0.001***
	CC	0.006**
	FD	0.034*
	KC	0.003**
	ED	0008**

As demonstrated by Tables 4.16 (a-c), significant differences between the river and drainage channel (p=<0.001***) and the river and ponds (p=<0.001***) were found. Concentrations in the river also varied, with higher TRP at the WTW (p=0.001) and NFM DP (p=0.005**) points compared to ST. This indicated the WTW as a point source for TRP pollution as concentrations were significantly higher in NFM DP than WD (p=<0.001***), rendering the NFM an unlikely source. The drainage channel also contained a significant variation with higher concentrations of TRP in ED in comparison to CD (p=0.002**) and WD (p=<0.001***). Additionally, P1, WD and CD were each significantly different to WTW, NFM DP, CC, FD, KC and ED demonstrating TRP was significantly higher in ED, P2 and the river. No other significant differences were found.

Spatial and Seasonal Variation Across the Catchment

Figure 4.10 and Tables 4.17 (a) and (b) outline a summary of the TRP across the catchment and the status of each site and waterbody based on 6-months of data.

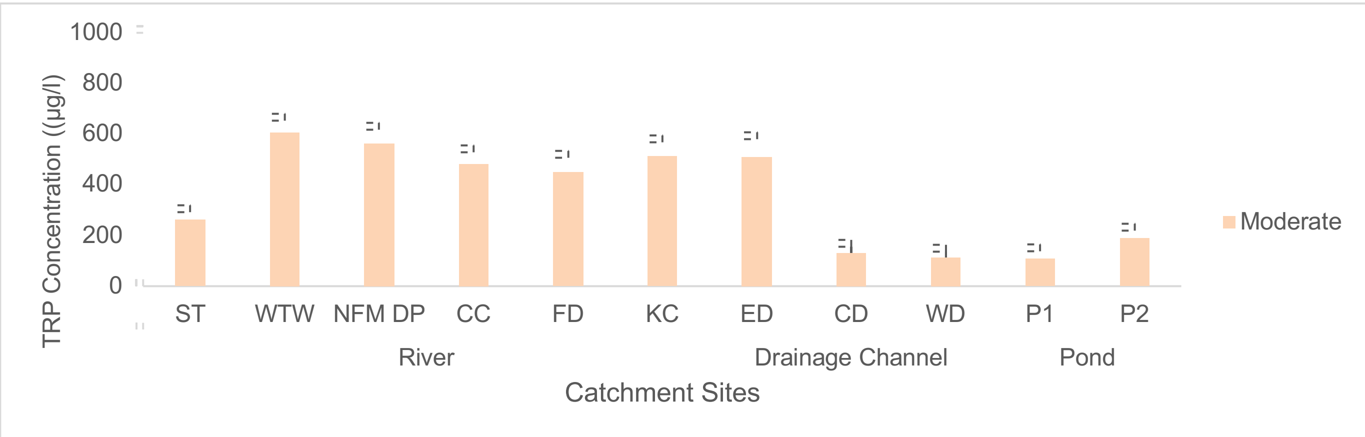

Figure 4.10: Average TRP (µg/l) of the Arrow catchment over 6 months and status according to WFD-UKTAG standards (+/- 1 SE).

Table 4.17 (a): 6-month summary of the variation in TRP across individual sites.

Test	ST	WTW	NFM DP	CC	FD	KC	ED	CD	WD	P1	P2
Mean	263	605	564	481	450	512	510	131	114	109	189
SD	98.8	181.8	198.5	171.4	188.4	187.7	234.9	80.7	75.7	94.0	97.7
Status	M	M	M	M	M	M	M	M	M	M	M
Seasonal Variation – Mann-Whitney U											
Spring	209	608	573	491	509	551	575	79	51	42	156
Summer	308	603	554	472	361	479	456	183	177	175	222
P-Value	0.082	1.000	0.202	0.589	0.352	0.537	0.329	0.041*	0.002**	0.009**	0.394

Table 4.17 (b): 6-month summary of the variation in TRP across the catchment.

Test	River Arrow	Drainage Channel	Ponds
Mean	483	244	149
SD	200.7	231.5	102.3
Status	M	M	M

As outlined in Tables 4.17 (a) and (b), all sites were classified as 'Moderate' quality based on the 6-month averages. Although the moderate quality threshold was not exceeded, the data shows a gradual increase in TRP over time, which if continued is likely to degrade the quality to poor and impact the annual classification. TRP was also unstable, most likely due to the WTW, with a significant standard deviation across the catchment. Although TRP concentrations decreased after the WTW, no significant difference between WTW and NFM DP (p=1.000) was found. There was also no significant difference between the NFM DP and CC (p=1.000) suggesting no significant discharge of TRP was sourced from the NFM. Furthermore, TRP was significantly lower in spring than summer in CD (p=0.041*), WD (p=0.002**) and P1 (p=0.009**) suggesting the NFM was successful in shielding and filtering contaminants.

<u>Temporal Variation</u>

Table 4.18: 2019 6-month TRP status and official historical catchment status classifications.

Waterbody	6-Month Classification	Past EA Catchment Status Classifications for TRP – Arrow*
River Arrow	Moderate	Poor (Cycles 1&2)
Main NFM Drainage Channel	Moderate	
Pond	Moderate	
*Official EA catchment status classifications only include the main River Arrow and its tributaries		

As demonstrated by Table 4.18, the 'Moderate' status found during the 6-months of monitoring suggests a marginal improvement as the Arrow Catchment has historically been classified as poor and failed to meet targets due to phosphate discharge from sewage effluents.

4.3.6. Total Nitrate (TN)

The nitrate concentrations detected in the Arrow catchment are outlined in Figures 4.11 (a-c).

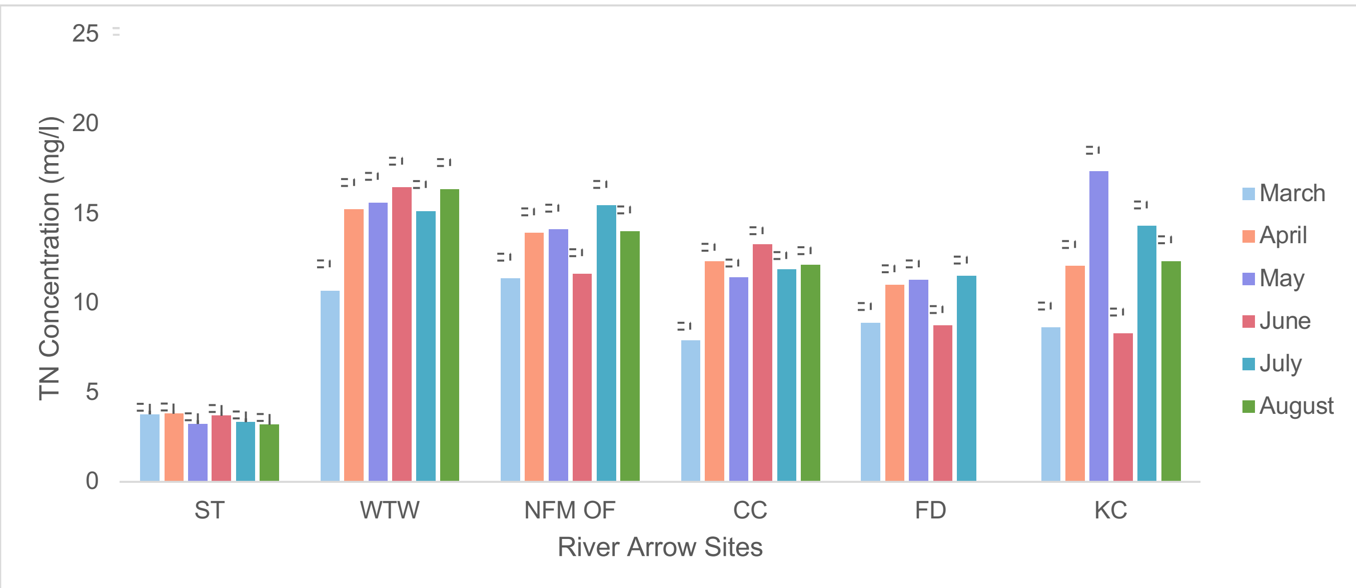

Figure 4.11 (a): Average monthly TN (mg/l) of the main River Arrow over 6 months (+/- 1 SE).

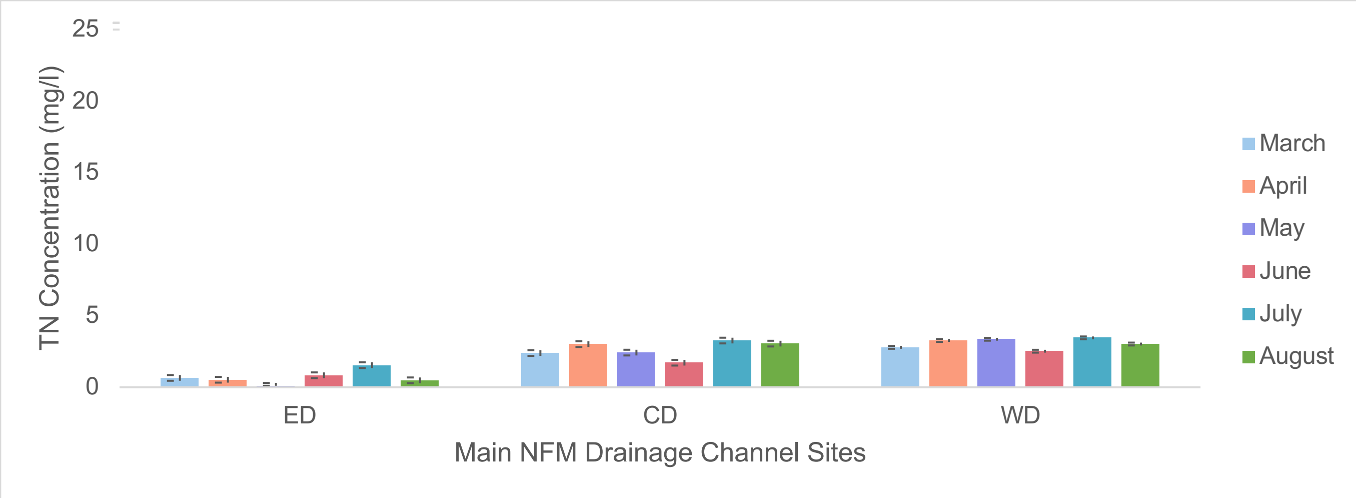

Figure 4.11 (b): Average monthly TN (mg/l) of the main NFM drainage channel over 6 months (+/- 1 SE).

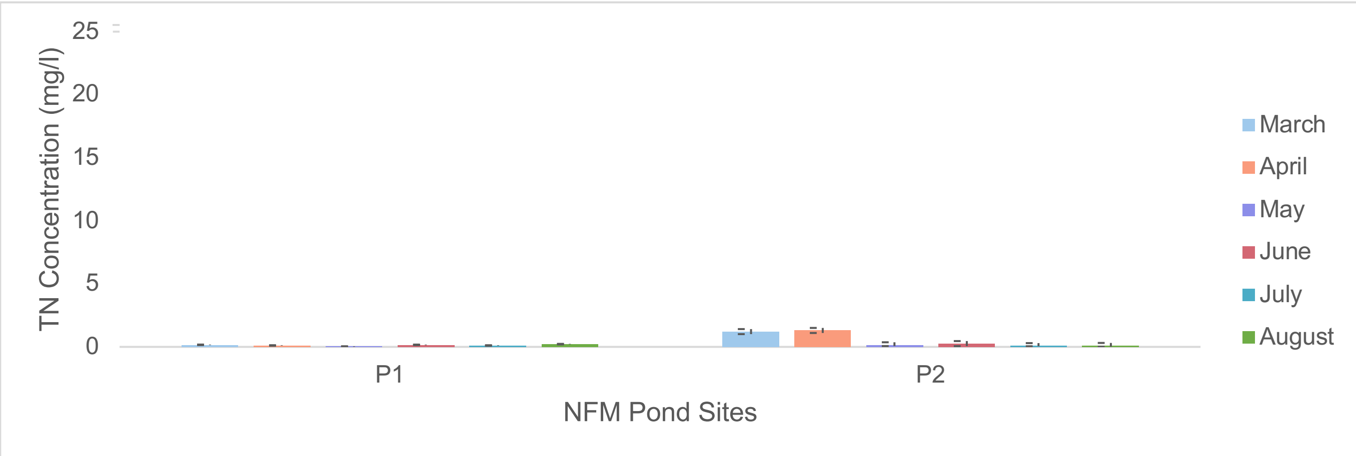

Figure 4.11 (c): Average monthly TN (mg/l) of the NFM ponds over 6 months (+/- 1 SE).

As demonstrated by Figures 4.11 (a), TN in the River Arrow varied significantly (p=<0.001***). Nitrate remained stable at c. 4mg/l in ST and dramatically increased at the WTW close to the 25mg/l threshold of concern. Concentrations steadily declined as the river flowed south, before significantly increasing at KC, after the end of the plantation influence. However, as demonstrated by Figures 4.11 (b) and (c), TN was significantly lower within the NFM, as the drainage channel and ponds both contained significantly lower levels of nitrate. The drainage channel did not exceed 4mg/l at any point; however, a slight increase was noted as the stream flowed west. Furthermore, TN concentration in the ponds was consistently low and did not exceed 2mg/l.

Significant differences Between Sites

Tables 4.19 (a-c) outline significant differences between sites.

Table 4.19 (a): Kruskal-Wallis/Mann-Whitney-U (ponds) results (TN) – within waterbodies.

Location	**P-Value**
River Arrow	<0.001***
Drainage Channel	<0.001***
Ponds	0.076

Table 4.19 (b): Kruskal-Wallis results (TN) – between waterbodies.

Location		P-Value
Overall Catchment		<0.001***
Post-Hoc Multiple Comparisons		
River Arrow	Drainage Channel	<0.001***
	Ponds	<0.001***
Drainage Channel	Ponds	0.020*

Table 4.19 (c): Kruskal-Wallis significant results (TN) – individual sample sites.

Location		P-Value
Overall Catchment		<0.001***
Post-Hoc Multiple Comparisons		
ST	WTW	0.016*
	NFM DP	0.039
ED	CD	0.002**
	WD	<0.001***
CD	WTW	0.003**
	NFM DP	0.011*
	KC	0.003**
WD	WTW	0.014*
	NFM DP	0.047*
ED	WTW	<0.001***
	NFM DP	<0.001***
	CC	<0.001***
	FD	0.003**
	KC	<0.001***
	ED	<0.001***
P1 and P2	WTW	<0.001***
	NFM DP	<0.001***
	CC	<0.001***
	FD	<0.001***
	KC	<0.001***
	ED	<0.001***

As demonstrated by Tables 4.19 (a-c), significant variation across the catchment was found (p=<0.001***). TN concentrations were significantly higher in WTW (p=0.016*) and NFM DP (p=0.039*) in comparison to ST. As TN was also significantly higher at both NFM DP (p=<0.001***) and WTW (p=0.014*) than WD, the NFM is unlikely to be the source. In the drainage channel, TN was also significantly lower in ED compared to CD (p=0.002**) and WD (p=<0.001***). Multiple differences across the catchment were also found. P1, P2 and ED were significantly lower in TN concentration than WTW, NFM DP, CC, FD, KC. ST, CD and WD were also significantly lower than WTW and NFM DP but were similar in quality to the remainder of the river sites.

Spatial and Seasonal Variation Across the Catchment

Figure 4.12 and Tables 4.20 (a) and (b) outline a summary of the TN across the catchment and the proximity of each site and waterbody to the 25mg/l threshold based on 6-months of data.

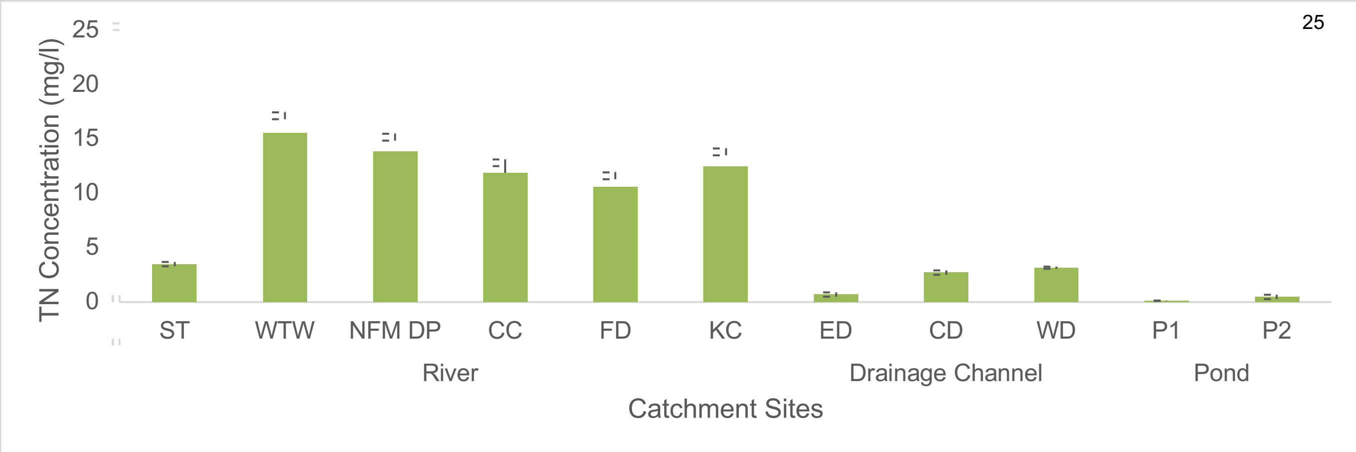

Figure 4.12: Average TN (mg/l) of the Arrow catchment over 6 months (+/- 1 SE).

Table 4.20 (a): 6-month summary of the variation in TN across individual sites.

Test	ST	WTW	NFM DP	CC	FD	KC	ED	CD	WD	P1	P2
Mean	3.5	15.5	13.8	11.9	10.6	12.5	0.7	2.7	3.2	0.1	0.5
SD	0.69	4.46	3.76	2.72	2.20	4.12	0.62	0.73	0.53	0.10	0.55
Status	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25
Seasonal Variation – Mann-Whitney U											
Spring	3.6	14.9	14.0	11.3	11.0	13.5	0.4	2.8	3.4	0.1	0.9
Summer	3.4	16.0	13.7	12.4	10.1	11.6	1.0	2.7	3.0	0.2	0.2
P-Value	0.329	0.310	0.343	0.485	1.000	0.247	0.082	1.000	0.589	0.394	0.065

Table 4.20 (b): 6-month summary of the variation in TN across the catchment.

Test	River Arrow	Drainage Channel	Ponds
Mean	11.1	2.2	0.3
SD	4.85	1.20	0.44
Status	<25	<25	<25

As outlined in Tables 4.20 (a) and (b), for the 6 months monitored, all sites averaged below the 25mg/l threshold for concern and the maximum limit of 50mg/l. However, concentrations peaked at 15mg/l at the WTW point which suggests the WTW was operating in proximity to the 15mg/l maximum limit for TN discharge (EA, 2019b). TN concentrations also remained stable over time as no significant difference between the spring and summer averages for any site was found, suggesting diffuse pollution and heavy rainfall is unlikely to be the source. The data also demonstrates that the concentration of TN in the river should be at the level observed at ST and a remediation for the WTW is necessary.

As nitrate is not currently monitored by the EA, temporal change in nitrate could not be assessed.

4.3.7. Total Ammonia (TA)

The TA concentrations detected in the Arrow catchment are outlined in Figures 4.13 (a-c).

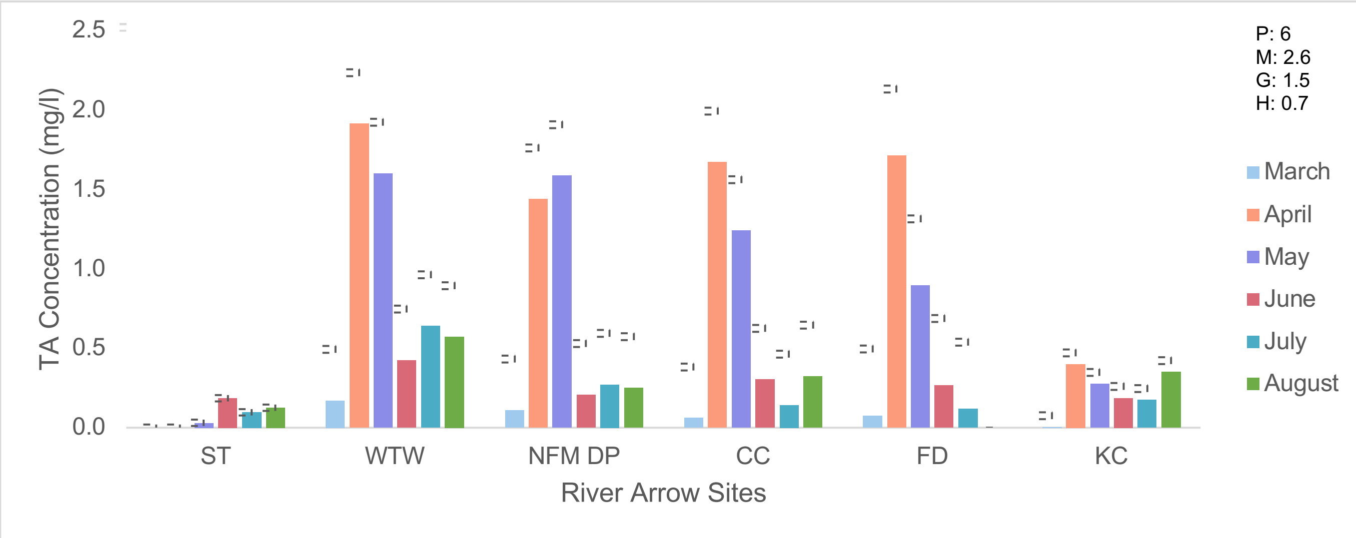

Figure 4.13 (a): Average monthly TA (mg/l) of the River Arrow over 6 months (+/- 1 SE).

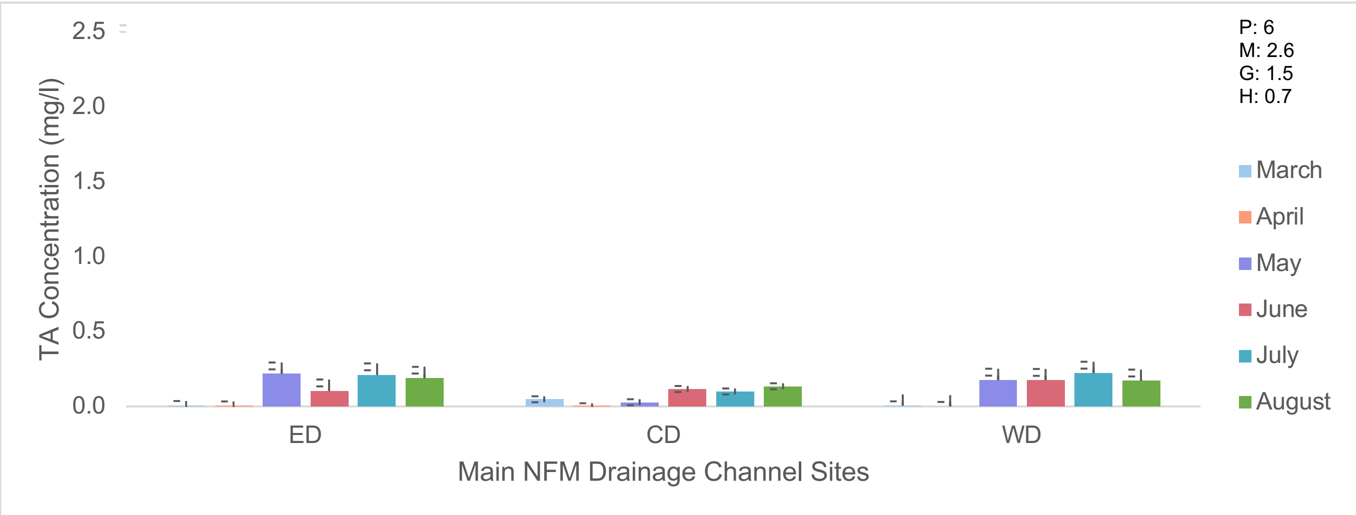

Figure 4.13 (b): Average monthly TA (mg/l) of the main NFM drainage channel over 6 months (+/- 1 SE).

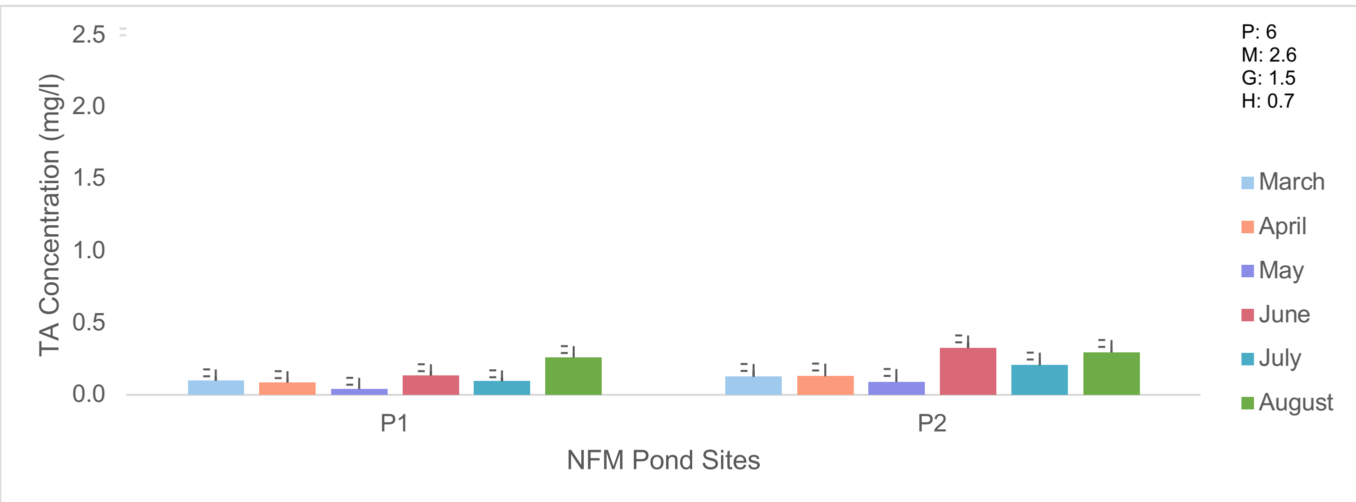

Figure 4.13 (c): Average monthly TA (mg/l) of the NFM ponds over 6 months (+/- 1 SE).

As demonstrated by Figures 4.13 (a-c), TA fluctuated significantly across the catchment. In the river, TA averaged below or near 0.5mg/l in all months with the exception of significant peaks in April and May at c. 1.5 -2mg/l. An increase in TA from ST to WTW was apparent, followed by a steady decrease as the river flowed south. TA was significantly more stable in the NFM waterbodies, remaining below 0.2mg/l in the drainage channel, rising slightly from ED to CD and falling from CD to WD. Ammonia remained below 0.4mg/l in the ponds and was slightly higher in P2 than P1.

Significant differences Between Sites

Tables 4.21 (a-c) outline significant differences between sites.

Table 4.21 (a): Kruskal-Wallis/Mann-Whitney-U (ponds) results (TA) – within waterbodies.

Location	P-Value
River Arrow	<0.001***
Drainage Channel	0.141
Ponds	0.219

Table 4.21 (b): Kruskal-Wallis results (TA) – between waterbodies.

Location		P-Value
Overall Catchment		<0.001***
Post-Hoc Multiple Comparisons		
River Arrow	Drainage Channel	<0.001***
	Ponds	0.093
Drainage Channel	Ponds	0.539

Table 4.21 (c): Kruskal-Wallis significant results (TA) – individual sample sites.

Location		P-Value
Overall Catchment		<0.001***
Post-Hoc Multiple Comparisons		
WTW	ST	<0.001***
	ED	0.009**
	CD	<0.001***
	WD	0.013*
	P1	0.004**
CD	NFM DP	0.024*

As outlined in Tables 4.21 (a-c), significant differences between the river and drainage channel (p=<0.001***) were found, comprising differences between WTW and ED (p=0.009**), CD (p=<0.001***), WD (p=0.013*) and P1 (p=0.004**). A significant difference between the river sites ST and WTW (p=<0.001***) was also found. TA concentrations were significantly higher at the WTW point in all cases. A significant difference between CD and NFM DP (p=0.024*) was also found. Although TA concentrations remained at a harmful level at the NFM DP, concentrations were slightly lower in comparison to the WTW point. No other significant differences across the catchment were found.

Spatial and Seasonal Variation Across the Catchment

Figure 4.14 and Tables 4.22 (a) and (b) outline a summary of the TA across the catchment and the status of each site and waterbody based on 6-months of data.

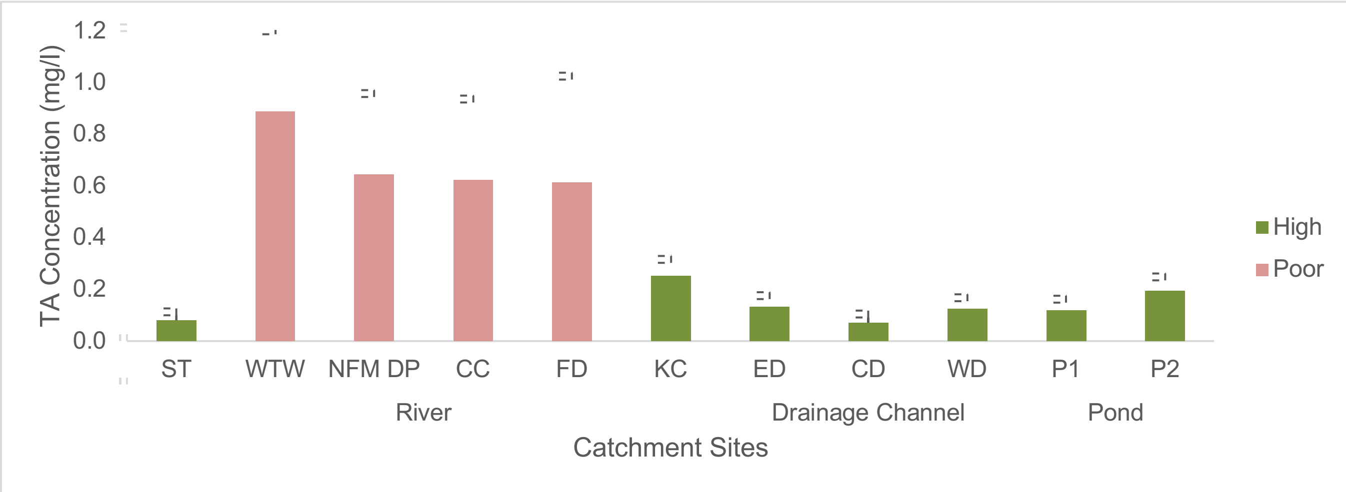

Figure 4.14: Average TA (mg/l) of the Arrow catchment over 6 months and status according to WFD-UKTAG standards (+/- 1 SE).

Table 4.22 (a): 6-month summary of the variation in TA across individual sites.

Test	ST	WTW	NFM DP	CC	FD	KC	ED	CD	WD	P1	P2
Mean	0.1	0.9	0.6	0.6	0.6	0.3	0.1	0.1	0.1	0.1	0.2
SD	0.08	0.96	1.01	1.03	1.08	0.10	0.11	0.05	0.10	0.10	0.14
Status	H	P	P	P	P	H	H	H	H	H	H
Seasonal Variation – Mann-Whitney U											
Spring	0.0	1.2	1.0	1.0	0.9	0.3	0.1	0.0	0.1	0.1	0.1
Summer	0.1	0.5	0.2	0.3	0.2	0.2	0.2	0.1	0.2	0.2	0.3
P-Value	0.017*	0.818	0.818	1.000	0.762	1.000	0.177	0.015*	0.093	0.240	0.026*

Table 4.22 (b): 6-month summary of the variation in TA across the catchment.

Test	River Arrow	Drainage Channel	Ponds
Mean	1	0	0
SD	0.85	0.09	0.13
Status	P	H	H

As Total Ammonia is a 99-percentile standard, no samples can exceed the standard threshold more than 1% of the time to achieve the status. Therefore, as ST, KC, the main drainage channel and both ponds did not exceed 0.5mg/l at any point, they are therefore classified as ‘High’. However, as WTW, NFM DP, CC and FD exceeded both the high and moderate limits more than 1% of the time likely due to stormwater events, they are classified as ‘Poor’. Therefore, due to these peaks, the River Arrow also classifies as ‘Poor’ with the highest standard deviation and fluctuation. Furthermore, significant differences between spring and summer were noted in ST (p=0.017*), CD (p=0.015*) and P2 (p=0.026*) in which TA was lower in spring than summer. No other significant difference between seasons was found.

Temporal Variation

Table 4.23: 2019 TA status and official historical catchment status classifications.

Waterbody	6-Month Status	Past EA Catchment Status Classifications for TA – Arrow*		
River Arrow	Poor	Poor 2012-2013	Moderate 2014	Good 2015-2016
Main NFM Drainage Channel	High			
Pond	High			
*Official EA catchment status classifications only include the main River Arrow and its tributaries				

As demonstrated by Table 4.23, the TA status of the catchment improved from 'Poor' in 2012-2013, to 'Moderate' in 2014 and 'Good' in 2015-2016, suggesting the NFM could possibly be having a positive impact. However, the data collected for this project classifies the river as 'Poor' based on 6 months of data due to contaminant peaks likely caused by stormwater as possibly a discharge of effluents from the WTW. It is possible that the final status for the year is improved based on a larger number of samples, increasing the number of allowable exceedances of the standards.

4.3.8. Specific Pollutants (SP) and Priority Substances (PS)

The SP and PS concentrations detected in the Arrow catchment are outlined in Figures 4.15 (a-c) and Tables 4.24 (a-d). Non-regulated nutrients are tabulated in mg/l due to significantly higher concentrations and are graphed in µg/l for visual consistency.

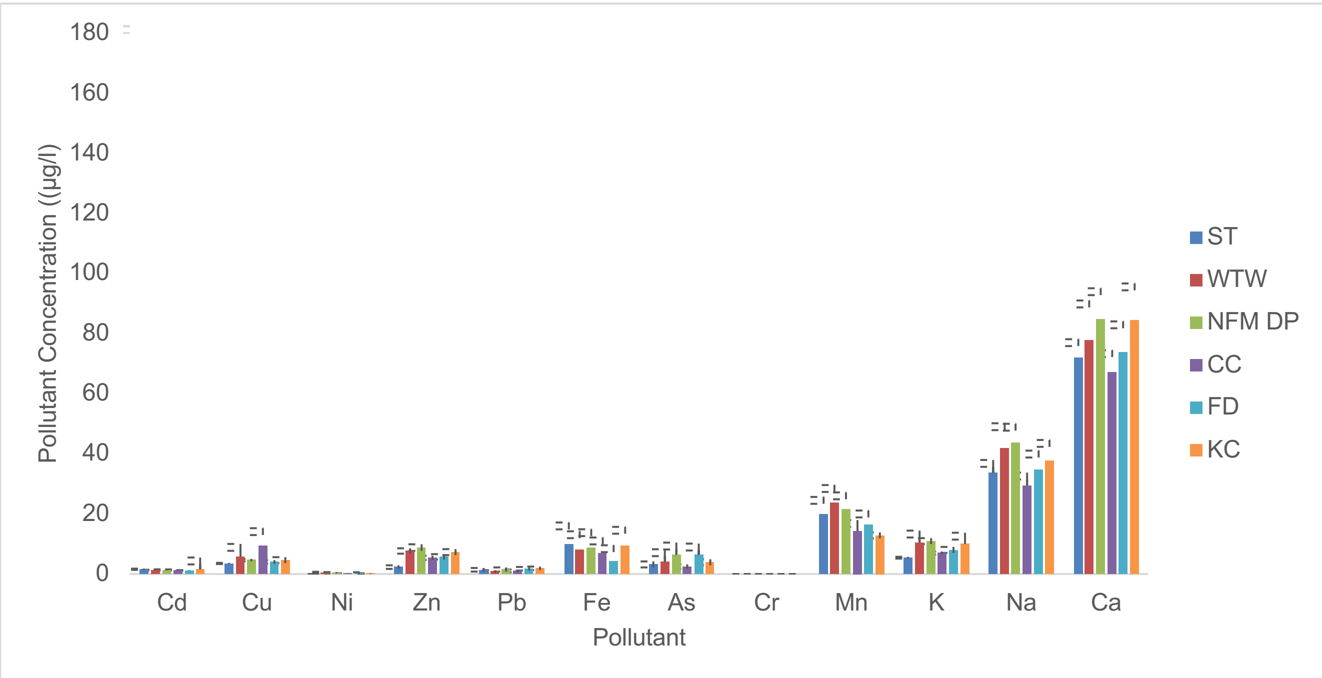

Figure 4.15 (a): Average monthly pollutants/nutrients (µg/l) of the River Arrow over 6 months (+/- 1 SE).

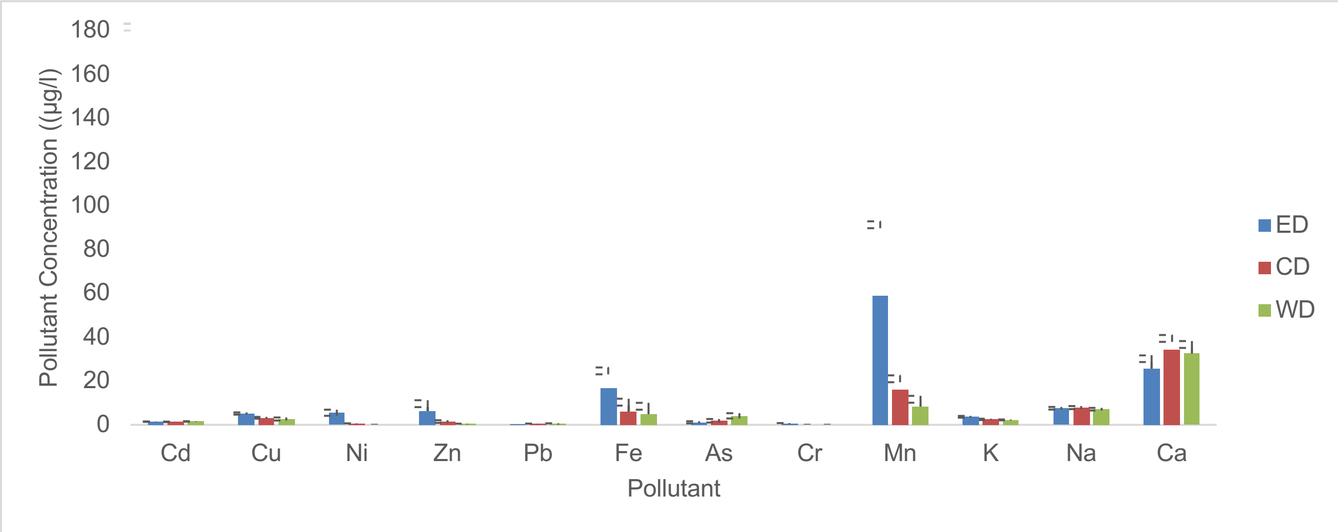

Figure 4.15 (b): Average monthly pollutants/nutrients (µg/l) of the main NFM drainage channel over 6 months (+/- 1 SE).

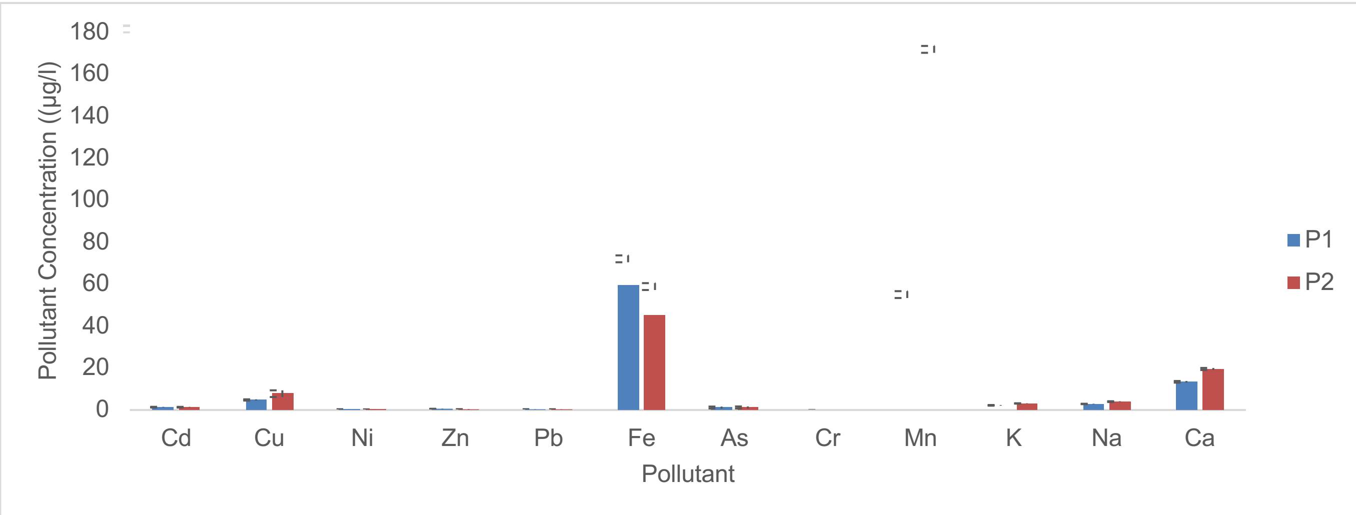

Figure 4.15 (c): Average monthly pollutants/nutrients (µg/l) of the NFM ponds over 6 months (+/- 1 SE).

Table 4.24 (a): 6-month summary of the variation in pollutants/nutrients across individual sites – ICP Results.

Regulated Specific Pollutants (ICP Results) (WFD-UKTAG, 2014c) (µg/l)										Non-Regulated Nutrients (mg/l)		
Site	**Cd**	**Cu***	**Ni***	**Zn***	**Pb**	**Fe**	**As**	**Cr III**	**Mn***	**K**	**Na**	**Ca**
River Arrow										**River Arrow**		
ST	2	4	0	2	1	10	3	0	20	5	34	72
WTW	1	6	0	8	1	8	4	0	24	11	42	78
NFM DP	1	5	0	9	2	9	6	0	22	11	44	85
CC	1	9	0	5	1	7	2	0	14	7	29	67
FD	1	4	0	6	2	4	6	0	16	8	35	74
KC	2	5	0	7	2	9	4	0	13	10	38	84
Drainage Channel										**Drainage Channel**		
ED	1	5	6	6	0	17	1	0	59	4	8	26
CD	1	3	0	1	0	6	2	0	16	2	8	34
WD	2	3	0	0	0	5	4	0	8	2	7	33
Ponds										**Ponds**		
P1	1	5	0	0	0	59	1	0	44	2	3	13
P2	1	8	0	0	0	45	1	0	134	3	4	20

Table 4.24 (b): 6-month summary of the variation in pollutants/nutrients across the catchment – ICP Results.

	Regulated Specific Pollutants (WFD-UKTAG, 2014) (µg/l)									Non-Regulated Nutrients (mg/l)		
Waterbody	**Cd**	**Cu***	**Ni***	**Zn***	**Pb**	**Fe**	**As**	**Cr III**	**Mn***	**K**	**Na**	**Ca**
River Arrow	1	5	0	6	1	8	4	0	18	9	37	77
Drainage Channel	1	4	2	3	0	9	2	0	28	3	8	31
Ponds	1	6	0	0	0	52	1	0	89	3	3	16

Table 4.24 (c): 6-month summary of the variation in bioavailable pollutants across individual sites.

Bioavailable Pollutants (µg/l)											
Pollutant	**ST**	**WTW**	**NFM DP**	**CC**	**FD**	**KC**	**ED**	**CD**	**WD**	**P1**	**P2**
Cu	0.1	0.2	0.1	0.3	0.1	0.2	0.2	0.1	0.1	0.1	0.2
Ni	0.0	0.1	0.1	0.0	0.1	0.0	1.5	0.1	0.0	0.1	0.0
Zn	0.6	2.3	2.6	1.5	1.6	2.1	1.8	0.4	0.1	0.1	0.1
Mn	12.5	5.9	6.0	9.2	5.9	5.2	28.7	15.3	8.4	24.0	56.1

Table 4.24 (d): 6-month summary of the variation in bioavailable pollutants across the catchment.

Bioavailable Pollutants (µg/l)				
Waterbody	**Cu***	**Ni***	**Zn***	**Mn***
River Arrow	0.2	0.0	1.8	7.5
Drainage Channel	0.1	0.5	0.8	17.5
Ponds	0.2	0.1	0.1	40.0

The data in Tables 4.24 (a) and (b) demonstrate that a range of toxic pollutants were present across the catchment. It was found that concentrations of Ni, Zn, Pb, As and Cr III did not exceed the maximum average or tolerance at any point. In addition, although Cd exceeded the maximum average and tolerance for ST, KC and WD, it was not detrimental to the quality of the river or drainage channel as a unit. However, high concentrations Fe (limit far exceeded but with a gentle decline) K, Na and Ca were found across the catchment. Furthermore, the data in Tables 4.24 (c) and (d) demonstrate the bioavailability of Cu, Ni, Zn and Mn calculated using the WFD-UKTAG Metal Bioavailability Assessment Tool (WFD-UKTAG, 2014a). It was found that none of the bioavailable concentrations of any of these pollutants exceeded the maximum tolerance limit.

Kruskal-Wallis Comparisons of the Catchment

It was found that concentrations of Zn, Pb, K, Na and Ca were significantly higher in the River Arrow in comparison to the main drainage channel (p=<0.001***) and ponds (p=<0.001***). Furthermore, concentrations of Cu, Fe, and Mn were significantly higher in concentration in the ponds in comparison to the River Arrow (p=<0.001***) and main drainage channel (p=<0.001***). Finally, Ar was significantly higher in the river than the ponds (p=0.002**).

Kruskal-Wallis Individual Comparisons of Waterbodies

Significant differences within the River Arrow, drainage channel and ponds were found for several contaminants. Within the river, concentrations of Zn were significantly higher at WTW (p=<0.0001***), NFM DP (p=<0.001***) and KC (p=0.009**) in comparison to ST. Concentrations of K were also significantly higher at WTW (p=0.026**) and NFM DP (p=0.002**) in comparison to ST. Within the drainage channel, it was found that concentrations of Cu were significantly higher in ED than WD (p=0.002**) and concentrations of Ni were also significantly higher in ED than CD (p=0.003**) and WD (p=<0.001***). Concentrations of Zn were also significantly higher in ED than CD (p=0.048*) and WD (p=0.006) and concentrations of K were significantly higher in ED than WD (p=0.048*). Finally, within the ponds, concentrations of Cu (p=0.001***), Mn (p=0.024*), K (p=<0.001***), Na (p=<0.001***) and Ca (p=<0.001***) were significantly higher in P2 than P1.

Seasonal Variation – Mann-Whitney-U

Several significant variations in season were identified across the catchment (refer to Appendix H for full supporting data and statistics). It was found that Cu, Ni, Zn, Pb, As and Na were significantly higher in spring than summer, likely due to stormwater activity. However, Fe, Mn, K and Ca were significantly higher in summer. Most notably, Fe increased from 0μg/l in spring to >10μ/l in summer.

4.3.9. Suspended Solids (SS)

The suspended solids detected in the Arrow catchment are outlined in Figures 4.16 (a-c).

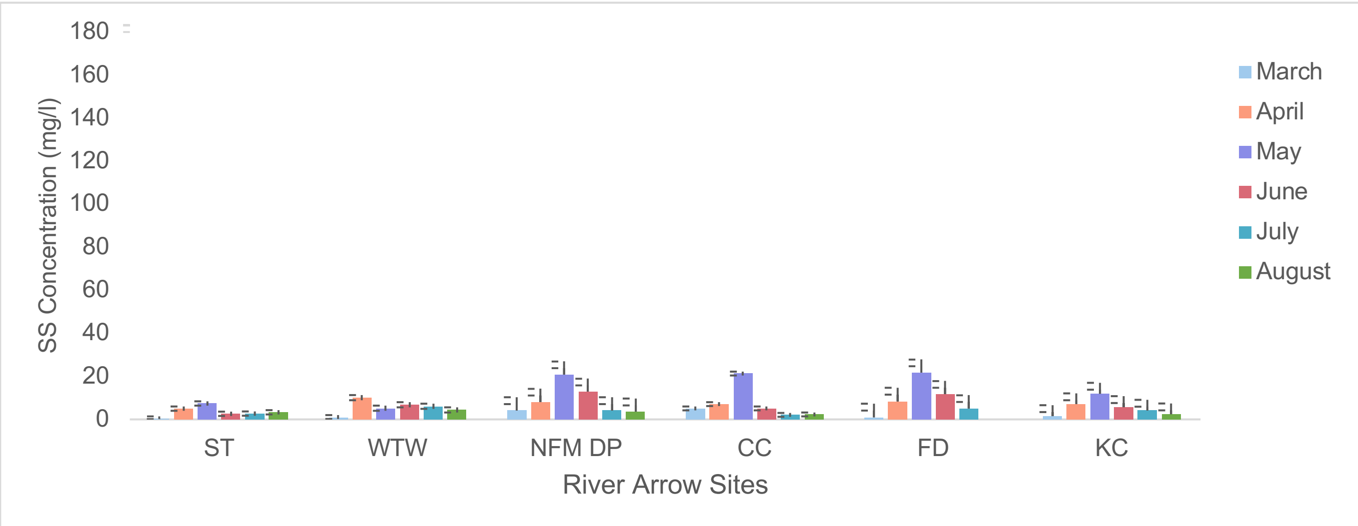

Figure 4.16 (a): Average monthly SS (mg/l) of the River Arrow over 6 months (+/- 1 SE).

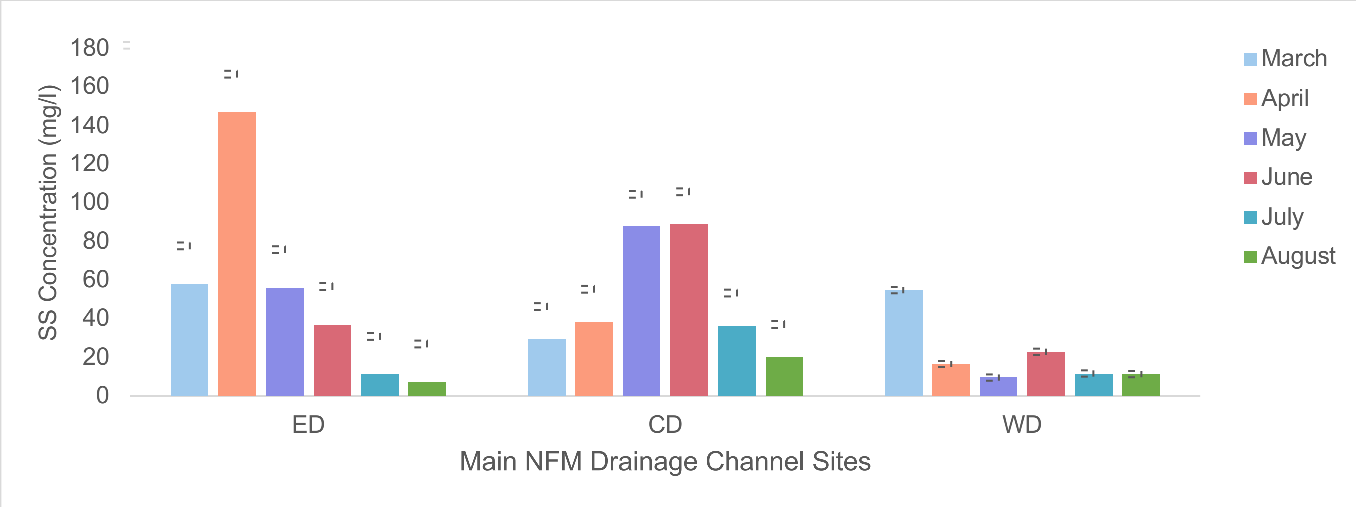

Figure 4.16 (b): Average monthly SS (mg/l) of the main NFM channel over 6 months (+/- 1 SE).

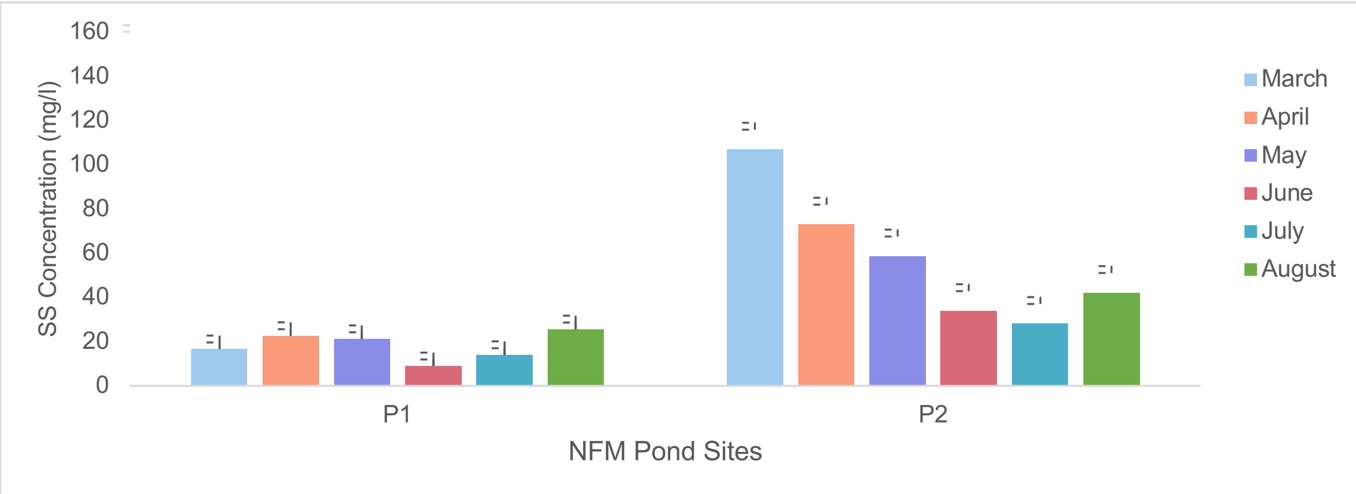

Figure 4.16 (c): Average monthly SS (mg/l) of the NFM ponds over 6 months (+/- 1 SE).

As demonstrated by Figures 4.16 (a-c) concentrations of suspended solids vary across the catchment. Although peaks of sediment likely caused by stormwater were observed in the River Arrow, concentrations remained below 25mg/l in all cases. However, in the smaller, shallow and slow flowing drainage channel significantly higher concentrations were observed in the eastern and central extents from c. 10-140mg/l, with much lower levels of mostly <20mg/l in the western extent. Finally, concentrations in P1 remained below 20mg/l with significantly higher concentrations from 25-100mg/l detected in P2. A mostly decreasing trend was observed across the catchment over time.

Significant differences Between Sites

Tables 4.25 (a-c) outline significant differences across the catchment.

Table 4.25 (a): Kruskal-Wallis/Mann-Whitney-U (ponds) results (SS) – within waterbodies.

Location	P-Value
River Arrow	0.312
Drainage Channel	0.096
Ponds	<0.001**

Table 4.25 (b): Kruskal-Wallis multiple comparisons results (SS) – between waterbodies.

Location		P-Value
Overall Catchment		<0.001***
Post-Hoc Multiple Comparisons		
River Arrow	Drainage Channel	<0.001***
	Ponds	<0.001***
Drainage Channel	Ponds	1.000

Table 4.25 (c): Kruskal-Wallis multiple comparisons significant results (SS) – individual sample sites.

Location		P-Value
Overall Catchment		<0.001***
Post-Hoc Multiple Comparisons		
ED	ST	0.001***
	WTW	0.023*
	CC	0.014*
	KC	0.015*
CD	ST	<0.001***
	WTW	0.001***
	NFM DP	0.013*
	CC	0.001***
	KC	0.001***
WD	ST	0.021
P1	ST	0.030
P2	ST	<0.001***
	WTW	<0.001***
	NFM DP	0.002**
	CC	<0.001***
	FD	0.009**
	KC	<0.001***

As outlined in Tables 4.25 (a-c), significant variation across the catchment was identified. The drainage channel and ponds contained significantly more suspended solids than the river, with WD and P1 containing the least of the NFM sites and were only significantly different to ST (p=0.021*), which had the lowest concentration of all sites. It is likely WD contained the least of the drainage channel sites due to attenuation behind the bridges. It was also found that P2 contained significantly more SS than P1 and all river sites due to waterfowl presence.

Spatial and Seasonal Variation Across the Catchment

Figure 4.17 and Tables 4.26 (a) and (b) outline a summary of the SS across the catchment and the status of each site and waterbody based on 6-months of data.

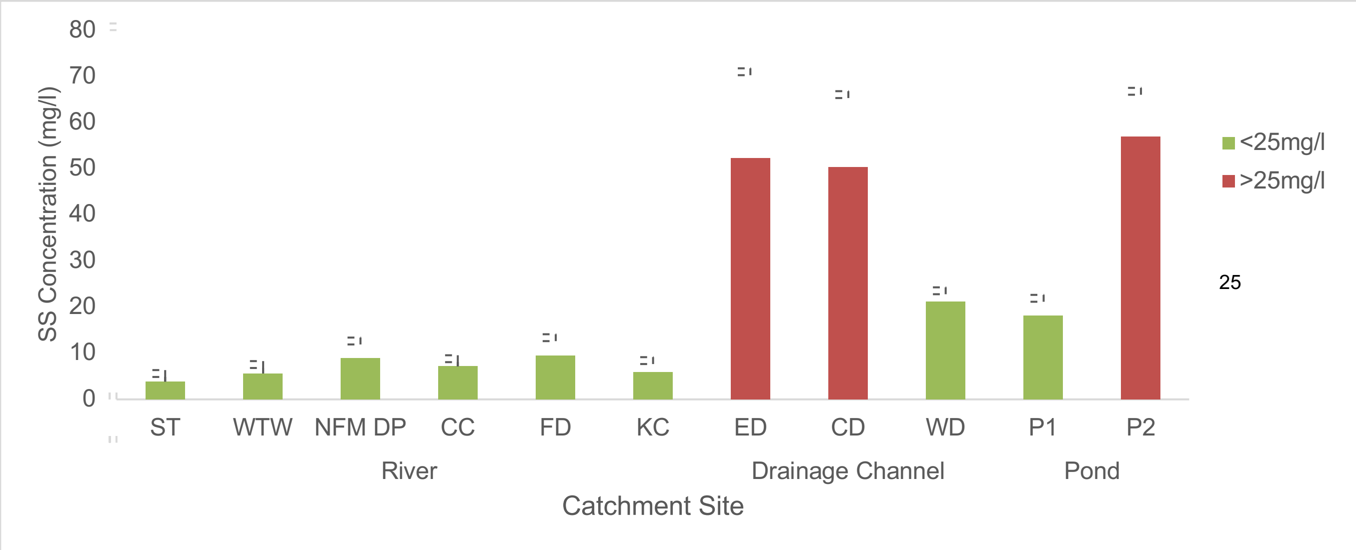

Figure 4.17: Average SS (mg/l) of the Arrow catchment over 6 months and status according to WFD-UKTAG standards (+/- 1 SE).

Table 4.26 (a): 6-month summary of the variation in SS across individual sites.

Test	ST	WTW	NFM DP	CC	FD	KC	ED	CD	WD	P1	P2
Mean	4	6	9	7	10	6	52	50	21	18	57
SD	3.35	3.94	9.77	10.31	9.36	6.01	60.42	48.34	23.53	9.63	32.73
Status	<25	<25	<25	<25	<25	<25	>50	≥50	<25	<25	>50
Seasonal Variation – Mann-Whitney U											
Spring	5	5	11	11	10	8	93	52	27	20	79
Summer	3	6	7	3	8	4	18	49	15	16	35
P-Value	0.662	0.589	0.639	0.093	0.762	1.000	0.030*	0.818	0.937	0.310	0.015*

Table 4.26 (b): 6-month summary of the variation in SS across the catchment.

Test	River Arrow	Drainage Channel	Ponds
Mean	7	41	38
SD	7.63	47.10	30.83
Status	<25	>25	>25

As demonstrated by Tables 4.26 (a) and (b), in 6 months, the River Arrow, P1 and WD did not exceed 25mg/l and are therefore not of concern. However, ED, CD and P2 contained an average of 50-57mg/l due to the shallow nature of the waterbodies and the presence of waterfowl in P2. Therefore, it is likely aquatic life will struggle to survive in these areas. However, suspended solids in ED and CD were not retained in WD due to the filtration occurring at the bridge points and wildlife is able to recover and thrive.

4.4. Correlations Between Ecological and Physico-Chemical Indicators

Spearman's Rank testing identified two correlations between ecological and physico-chemical indicators. As demonstrated in Figures 4.18 and 4.19, positive correlations were identified between dissolved oxygen and NTAXA EQR (p=0.040*) and ASPT EQR and temperature (p=0.035*).

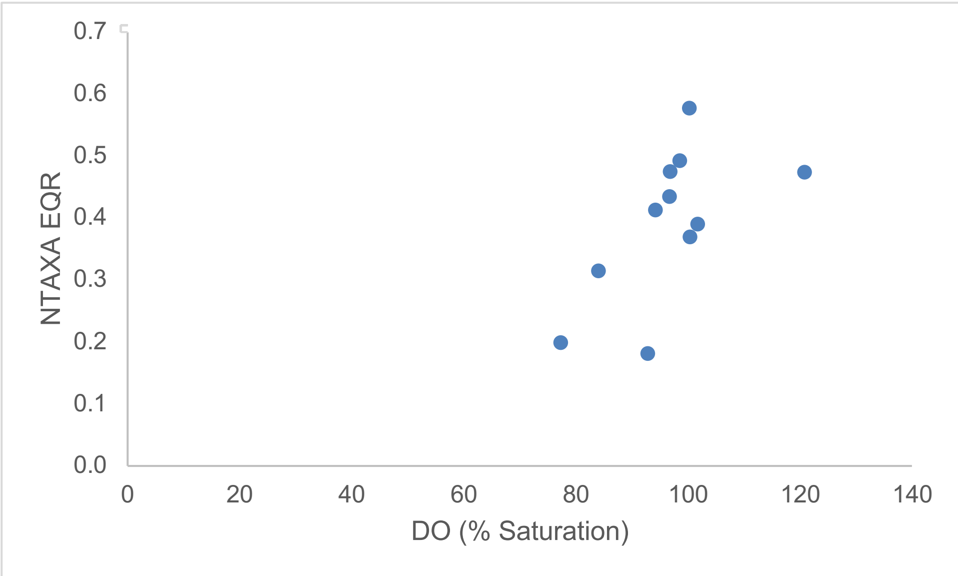

Figure 4.18: Correlation of NTAXA EQR and DO (% Saturation)

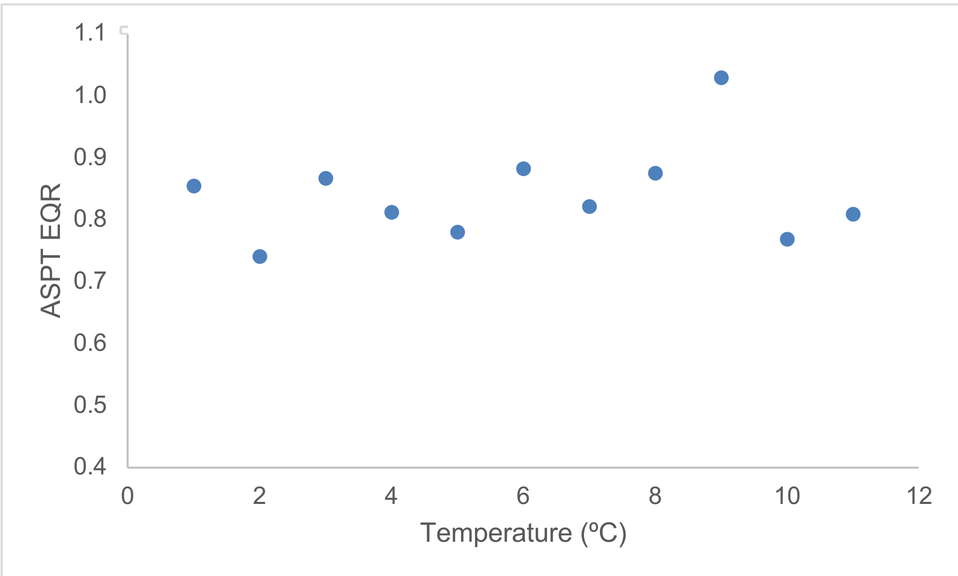

Figure 4.19: Correlation for ASPT and Temperature (ºC)

CHAPTER 5. DISCUSSION

To meet the aim and test the hypotheses of this research, a range of ecological and physico-chemical indicators were investigated over 6 months. This chapter will evaluate the research method and explore the key spatial and temporal ecological and physico-chemical findings across the Arrow catchment in order to infer the ecological potential and possible impact of the NFM scheme in the Arrow catchment.

5.1. Ecological Indicators

Figure 5.1 and Table 5.1 summarise the ecological quality of the Arrow catchment in 2019.

Summary of the Ecological Quality of the Arrow Catchment in 2019

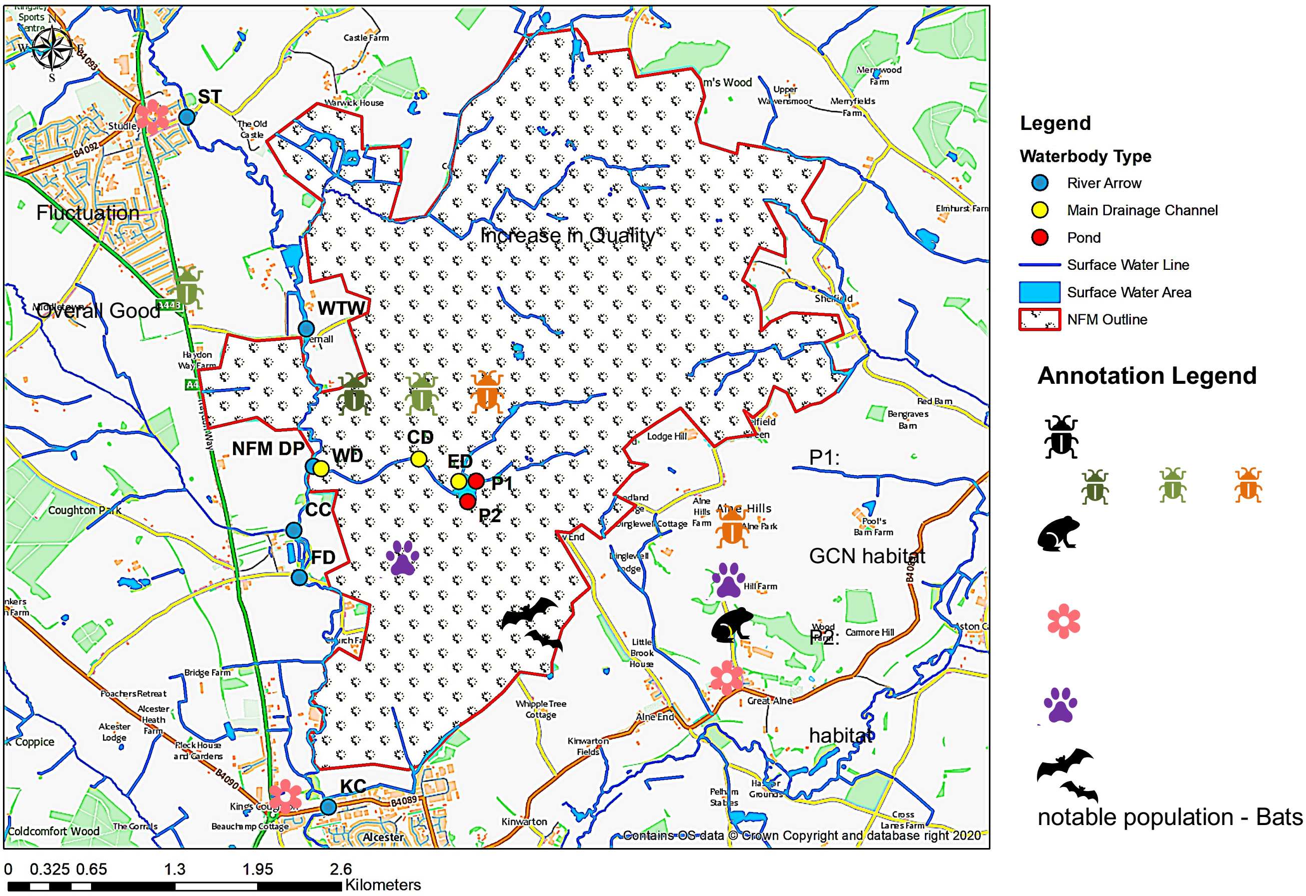

Figure 5.1: Summary of the ecological quality of the Arrow catchment in 2019.

Table 5.1: Summary of the ecological quality of the Arrow catchment in 2019.

Site	Botanical		HSI		Macroinvertebrates			
	H'	J'	P1	P2	NTAXA	ASPT	H'	J'
River Arrow	1.81	0.80	/	/	P	G	1.86	0.80
Drainage Channel	1.69	0.75	/	/	B	G	0.78	0.47
Ponds	1.85	0.76	Excellent	Good	B	G	1.51	0.79

Firstly, the data demonstrates that H' and J' scores across the catchment indicate a relatively diverse and evenly distributed floral and faunal (macroinvertebrate) community. Some spatial variation was observed as, for example, ST and KC were fringed by more mature woodlands, in contrast to sites adjacent to new plantations and open pasture. These findings support assertions within existing literature (e.g. Iacob *et al.*, 2014, SEPA, 2015; Short *et al.*, 2018) and provide evidence that plantations offer key habitat as the average diversity of the artificially planted and established NFM was similar to the main river and was therefore near-natural. The NFM also provided habitat for many protected and notable faunal species, as numerous mammal pathways were observed on site during field studies and significantly larger and more diverse populations were present after the implementation of the 2002-2017 plantations. It also proves increased canopy shade and riparian habitat provides shelter for aquatic flora and fauna as stated in the SEPA manual (2015). Additionally, the two ponds in the NFM contained the most diverse floral communities as they were fringed by large areas of naturally established terrestrial vegetation likely to provide new habitat. The ponds were diverse in aquatic fauna with 'Excellent' (P1) and 'Good' (P2) suitability for GCN in addition to observations of single GCN individuals, hundreds of breeding amphibians and small populations of moderate tolerance macroinvertebrates. This suggests artificial ponds and modified landscapes created for NFM schemes have the potential to support a range of species in conditions similar, if not superior to the natural environment if left to establish naturally. These findings support existing research into the habitat potential of NFM and SuDS installations and current assertions that water bodies such as detention basins, ponds, wetlands and soakaways may prove to be the most beneficial and encouraging for wildlife (SEPA, 2015; Woods Ballard, 2015).

The 'Poor' and 'Bad' status for macroinvertebrate NTAXA across the catchment indicates the communities present were limited in abundance and differed significantly from natural conditions, highlighting the impact of eutrophication and nutrient pollution (refer to Section 5.2) (WFD-UKTAG, 2013a). The Spearman's rank positive correlations between NTAXA/DO and ASPT/temperature also demonstrate taxa's dependence on higher quality conditions. Although communities are limited in number, ASPT scores demonstrate an average of 'Good' scoring taxa throughout the catchment, with some degradation and fluctuation around the WTW and CC, indicating taxonomic composition and diversity only slightly differed from undisturbed conditions and the ratio of sensitive to non-sensitive taxa only showed slight alteration from the type-specific conditions (WFD-UKTAG, 2013a). However, WD was the only individual site to classify as 'High' for ASPT, indicating taxonomic composition and diversity totally/nearly totally corresponded to undisturbed conditions (WFD-UKTAG, 2013a). The increase from 'Moderate' status in ED to 'Good' in CD and 'High' in WD clearly demonstrate a steady improvement of water quality as water flows across the NFM. The presence of high scoring, sensitive species in the western extent of the drainage channel suggests pollution at this point is minimal and high-quality water is discharged into the main river from the NFM, likely due to the settlement/filtration of pollutants as water is attenuated behind the bridges and the reduction in stormwater due to the presence of the plantations. These findings therefore support the conclusions made by Wenn (2008) and prove that the sensitivity of macroinvertebrate communities have the ability to highlight pollution events that frequent chemical testing may oversee, as the ASPT scores directly reflect physico-chemical conditions. These results also align with those of Le Viol *et* al. (2009) and Heal (2000), as thriving and viable communities were observed within the ponds, with evidence of minor/moderate pollution. However, the results disprove the assertion that ponds support higher numbers of rare taxa (e.g. Williams *et al.*, 2003; Biggs *et al*., 2005; Lukacs *et al*., 2013), as WD and some river sites contained more sensitive taxa.

5.2. Physico-Chemical Indicators

Figure 5.2 and Table 5.2 summarise the physico-chemical quality of the Arrow catchment in 2019.

Summary of the Physico-Chemical Quality of the Arrow Catchment in 2019

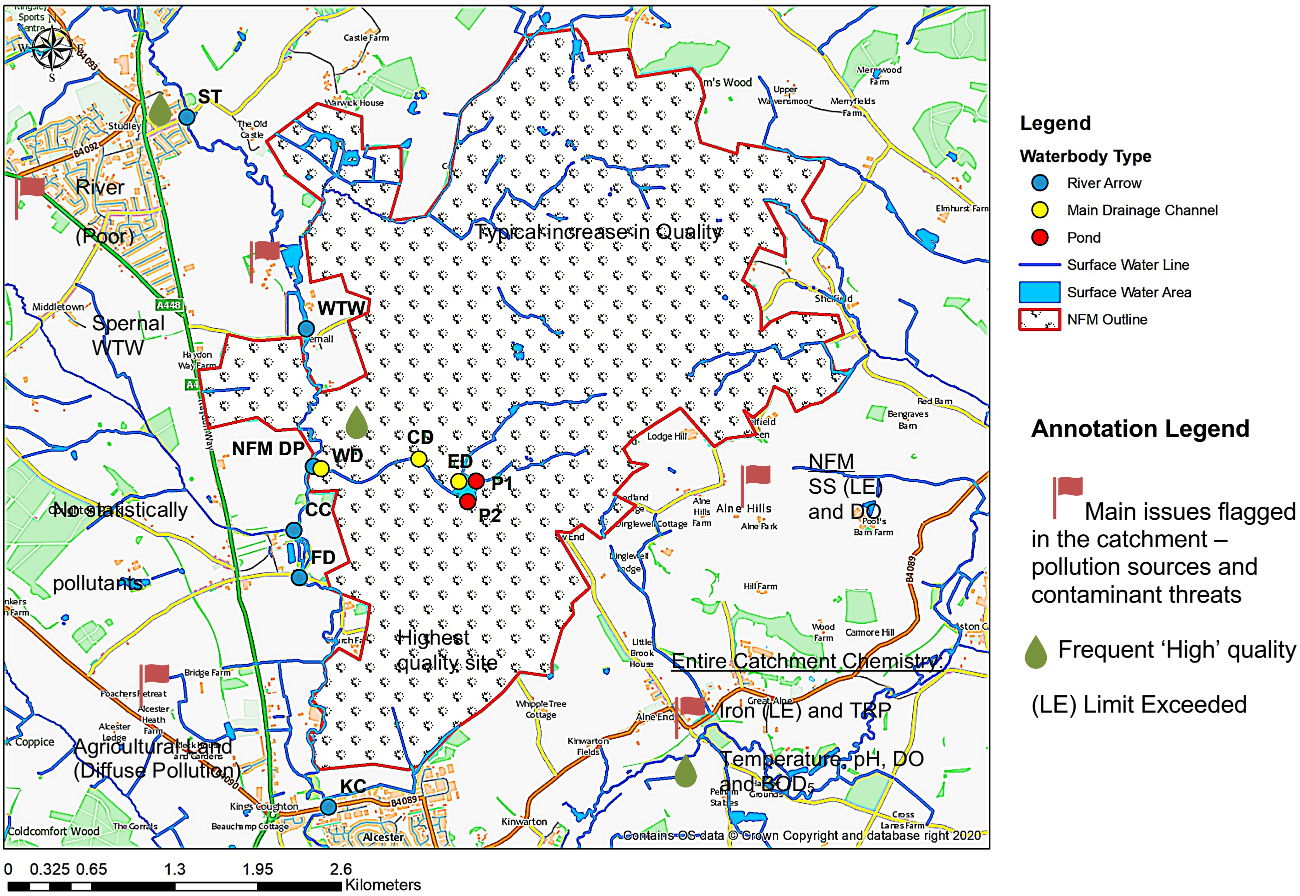

Figure 5.2: Summary of the physico-chemical quality of the Arrow catchment in 2019.

Table 5.2: Summary of the physico-chemical quality of the Arrow catchment in 2019.

Site	pH	Temp	DO	BOD_5	TRP	TN	TA	SS	SP/PS*
River Arrow	H	H	H	H	M	< 25	P	< 25	Fe
Drainage Channel	H	H	M	H	M	< 25	H	> 25	Fe
Ponds	H	H	H	H	M	< 25	H	> 25	Fe
*All other priority substances and specific pollutants did not exceed maximum tolerance.									

The data demonstrates that the Arrow Catchment varies in quality in relation to physico-chemistry. The catchment classified as 'High' quality for pH, Temperature, BOD_5 and Total Nitrate suggesting suitable conditions for aquatic communities to thrive, with minor nitrate pollution, plentiful oxygen availability and minimal oxidation of organic matter. This disproves conclusions made in the wider literature (e.g. Mitchell, 2005; Mallin and Cahoon, 2020), as BOD_5 concentrations were far below the point of failure found in many UK rivers and the high concentrations of phosphate did not significantly increase BOD_5. Dissolved oxygen was also 'High' in the river and ponds and 'Moderate' in the drainage channel due to size and slow flow in the eastern extent as CD and WD classified as 'High'. Suspended solids were also minimal in the river but a major issue for the drainage channel and ponds due to the size and shallow nature of the drainage channel and heavy waterfowl presence in P2. Although, suspended solids averaged below the 25mg/l threshold in WD and no significant increase in suspended solids was identified in the river, concentrations in WD increased to 80mg/l in storm events and it is likely to flush high concentrations of sediment into the river in more severe storm conditions. This contradicts the current assertions that NFM measures decrease the influx of suspended solids (e.g. Iacob *et al.,* 2014; Short *et* al., 2018) as outlined in Chapter 2, but supports the call for further research into excessive storm performance (Wilkinson *et al.,* 2019).

The results also highlight that high concentrations of Total Reactive Phosphorus and Fe (Iron) were a major issue for the catchment, which the NFM was unable to influence or improve as moderate – high concentrations were also located within the NFM waterbodies. Total Ammonia was also highlighted as a major issue in the main river which was classified as 'Poor' likely due to both the WTW and a stormwater event as ammonia does not remain in form for great distances, but was not of concern in the drainage channel and ponds. These findings reflect the conclusions of Barber & Quinn (2012), as their study of soft engineering approaches to flood management also concluded that nutrients such as TRP and suspended solids remained prevalent within the study area and further prevention methods were required. The conclusions of this project and those of other authors acknowledge the presence of a major issue in relation to nutrient loading. In areas impacted by eutrophication, many recent studies (e.g. Harrison *et al.,* 2019; Mallin and Cahoon, 2020) observed an increased frequency and severity of hypoxic events, harmful algal blooms, impacts to ecosystem function and stimulation of aquatic bacteria (increasing BOD). The findings also support the suggestion by Goddard *et al.* (2019) in which Fe and suspended solids influence variation in P concentrations, as elevated concentrations of both nutrients were identified. The conclusions of Vuori (1995) are also supported, as it is apparent the high concentrations of Fe may have triggered direct and indirect effects on river systems by increasing the toxicity of other substances (Sevcikova *et al.*, 2011; da Mata Pavione *et al*., 2019).

The negative impacts of nutrient loading reported within the literature are also supported by field observations of extensive algal blooms, moss and eutrophication within the river. However, no evidence of eutrophication was identified within the drainage channel or ponds suggesting a point source impacting only the river. This is evidenced by statistically significant increases in Total Reactive Phosphorus, Total Nitrate, Total Ammonia, Zn and K from ST to WTW, followed by steady re-equilibration. Significant decreases/degradation in pH and dissolved oxygen were also observed from ST to WTW, indicating the WTW as the most likely source of the elevated pollutants and degraded water quality of the catchment. It is likely that the issue of elevated pollutants will remain apparent within the catchment and it is unlikely that the NFM will be able to improve conditions or have any significant positive impact to the water quality of the catchment until a remediation scheme targeted at the WTW point source is in place (refer to Section 5.3 for further explanation). However, it is possible that the eutrophication of the river and elevated pollution caused by the WTW masked any minor impact the NFM may have had. Although this is unlikely as the NFM discharged predominantly high-quality water, is possible the addition of minor pollutants to a more sensitive high-quality river may have a slight impact.

Furthermore, a consistently improved quality was observed as runoff water flowed from east to west, as ED typically contained higher levels of pollution in the areas of higher elevation and older plantation before attenuating behind two bridge dams (one of which was located at CD) and discharging into the River Arrow from WD with typically 'High' quality. The statistical results also prove that no significant increase in any pollutant was present between the sites prior to, at or after the NFM discharge point, suggesting the NFM was successful in the filtration and protection from the majority of diffuse pollution and the NFM drainage channel did not act as a point source. These findings support conclusions made in the wider literature (as outlined in Chapter 2) and prove that NFMs did not have negative impact on water quality in the Arrow catchment and may possibly improve quality in areas impacted only by diffuse pollution (Iacob *et al.,* 2014; Wilkinson *et al.,* 2019). These findings also generally refute the conclusions made by Iacob *et al.* (2017) as several pollutants and parameters were of little/no concern, however, some elevated levels of phosphate were identified in the drainage channel.

5.3. Temporal Variation in Ecological and Physico-Chemical Indicators

5.3.1. Seasonal Variation

In similarity to other studies (e.g. Scholz, 2004; Zhang *et al.,* 2018), seasonal variation in indicators was identified between spring and summer. Several significant variations in specific pollutants were identified across the catchment, in which Cu, Ni, Zn, Pb, As and Na were significantly higher in spring than summer, likely due to stormwater activity. However, although peaks likely caused by stormwater were observed in spring for several other indicators, SS in P2 was significant. However, in contrast, concentrations of TRP, TA, Fe, Mn, K and Ca were significantly higher in summer. Most notably, Fe increased from 0µg/l in spring to >10 µ/l in summer.

5.3.2. Temporal Variation in Status

<u>Historical Variation from 2009-2019</u>

Table 5.3: Summary of water quality in the Arrow catchment over 10 years (data sourced from: EA, 2020a).

Year	Overall Official Status	Ecological Overall	Eco Element	Physico-Chemical Overall	Physico-Chemical Elements					
			Inverts		TA	BOD_5	DO	pH	Temp	TRP
Past Overall Status Classifications Cycle 1 (2009 – 2014) – EA Secondary Data (Official)										
2009	Moderate	Moderate	M	-	-	-	-	-	-	-
2010	Poor	Poor	P	-	-	-	-	-	-	-
2011	Moderate	Moderate	G	-	-	-	-	-	-	-
2012	Moderate	Moderate	-	Moderate	P	G	H	H	H	P
Past Overall Status Classifications Cycle 2 (2015 – 2021) – EA Secondary Data (Official)										
2013	Moderate	Moderate	M	Moderate	P	G	H	H	H	P
2014	Moderate	Moderate	G	Moderate	M	G	H	H	H	P
2015	Moderate	Moderate	G	Moderate	G	H	H	H	H	P
2016	Moderate	Good	G	Moderate	G	H	H	H	H	P
Primary Study Data – Status Classifications for River Arrow*										
2019	Unknown	Unknown	B H	Moderate	P	H	H	H	H	M
*Primary study data for 2019 is based on 6-month averages collected for the purposes of this research. Status classifications are not official. No data from 2016 onwards had been published at the date of writing.										

As discussed throughout Chapter 4, the EA data and primary data from 2019 demonstrated in Table 5.3 indicates an improvement in BOD_5, macroinvertebrates, TRP and TA over 10 years. However, TA and NTAXA were slightly degraded in 2019, possibly due to small sample sizes, sampling technique and sensitivity to the 99 percentile standards (TA). This indicates conditions for specific indicators within the catchment are improving, possibly due to the presence and influence of the NFM, as most of the plantations in proximity to the river were planted in 2010-2014 and as they mature may be beginning to impact the catchment quality. This is supported by the findings of studies outlined in the literature review such as Haygarth, 2010 and Wilkinson *et* al., 2014. These researchers concluded that a catchment management approach may be successful at reducing pollution, however, with the implementation of such large-scale schemes, it is likely to take several years to detect any change in the sediment and nutrient regime at the catchment scale. This appears to be true as no improvement in overall status of the catchment has been observed despite improvements in some parameters, likely due to the WTW. Therefore, further research and monitoring of consistent sites prior to and after the installation of NFM measures in catchments unaffected by or containing remediated point sources over an extended period will be needed to categorically prove this. Currently, limited data into this topic is available and the lack of and need for improved post-project monitoring has been highlighted by several other studies (e.g. Wenn, 2008; Cashman *et al.,* 2018).

<u>Targets and Predictions</u>

Table 5.4: Summary of water quality targets and predictions in the Arrow catchment (data sourced from: EA, 2020).

Year	Overall Official Status	Ecological Overall	Eco Element	Physico-Chemical Overall	Physico-Chemical Elements					
			Inverts		TA	BOD_5	DO	pH	Temp	TRP
Targets										
2015	Moderate	Moderate	G	-	G	-	G	G	G	-
2027	-	-	-	Good		-	-	-	-	G
Predictions										
2021	Moderate	Moderate	G	Moderate	G	-	H	H	H	M
2027	Moderate	Moderate	G	Good	-	-	H	H	H	G

As demonstrated by Table 5.4, the arrow catchment met targets for macroinvertebrates and TA and exceeded targets for DO, temperature and pH in 2015. It is also predicted to improve all physico-chemical elements from the current and 2021 predicted 'Moderate' to Good' by 2027, including TRP. This suggests that either a specific WTW remediation scheme is planned and was already highlighted by current catchment conditions or the NFM is expected to improve quality in the region by 2027. Therefore, further research and monitoring of this NFM should be carried out using the baseline set by this project and follow-up assessments made in 2027 to fully understand the impact and full potential of this particular NFM.

5.4. Factors Impacting Water Quality

5.4.1. Point Source Pollution – Water Treatment Works (WTW)

Although no exceedance of the 100mg/l SS limit, 25mg/l BOD limit or 15mg/l TN limit for WTWs was found (EA, 2018; EA, 2019), the findings of this research suggest the river was subject to heavy eutrophication, likely from the point source discharge of nutrients and other effluents from the WTW. The statistical findings suggest that ST was similar in quality to the NFM, therefore the concentration of pollutants should have been at the level observed at ST. This highlights the quality potential of the catchment and the necessity for a remediation scheme specifically targeted at the WTW to achieve this potential. Although no exceedance of the 2mg/l maximum phosphate limit (10,000-100,000 Population Equivalent) for WTWs operating within a eutrophic sensitive area (EA, 2019b; EA, 2020c; NextGen, 2018) was detected during this project, TRP, TA and Fe concentrations remained at a harmful level for aquatic life. Additionally, although Fe concentrations were beyond the 1mg/l limit (EA, 2018), Fe decreased from ST-WTW, indicating an alternative source. The need for remediation schemes in relation to the discharge of phosphorus, nitrate, ammonia and other nutrients from WTWs have been researched and tested in the past (refer to Chapter 2). For example, similarly to this project, Jarvie *et al.* (2006), observed high levels of phosphorus and eutrophication in the river Lambourn, Berkshire in proximity to a WTW. After mitigation, researchers observed a reduction in phosphorus and a subsequent release of phosphorus from river sediments as the system re-equilibrated. Similar results were also observed by Wenn (2008) as macroinvertebrate communities recovered after the implementation of a WTW remediation scheme. Furthermore, the 2014 updated 99 percentile standards for BOD and Ammonia were set by the WFD-UKTAG under the WFD with a specific aim to assess the need for further action in relation to WTW discharges (WFD-UKTAG, 2014c), further highlighting the need for specialised action.

5.4.2. Diffuse Pollution

The significant seasonal variation in several heavy metals and fluctuation of nutrients over time suggests the river remains influenced by diffuse pollution and stormwater effluents. These likely originated from the western agricultural land as no significant pollutants/sediments were discharged from the NFM to the east. However, a small increase in nitrate was noted within the central and western extents of the drainage channel, likely due to proximity to Middle Spernal Farm. Furthermore, despite the presence of the NFM, the catchment remains a Nitrate Vulnerable Zone (NVZ) (EA, 2020a), indicating that further action, expansion of the NFM and the implementation of imperative standards for nitrate is needed. It is also likely that strategies such as NFM should be used in conjunction with other factors and measures for true success. This point was also highlighted by Wilkinson *et* al. (2014), who concluded that catchment management approaches may be successful at reducing pollution, but required the cooperation of multiple stakeholders and residents, as management at the field and farm scale remains crucial to water quality outcomes.

5.5. Leaving the EU – Will this impact the UK's Target of 'Good' Status?

This project focuses on the parameters and standards as outlined by the WFD-UKTAG under the EU WFD, as the UK was a member state at the time of writing. Although the UK left the EU in 2020, it is the current understanding that from 1st January 2021 the UK will uphold, adapt and maintain international obligations and EU environmental standards such as water and protection of habitats and species via a new statutory body - The Office for Environmental Protection (OEP) (DEFRA and AJC, 2019). Environmental targets such as water quality standards were also already covered by UK law. Therefore, the standards, classifications and targets used throughout this project remain valid.

5.6. Method Evaluation

5.6.1. Field Methodology

Sample locations were selected after GIS analysis of flow accumulation and direction to ensure representative samples for the catchment water quality were collected. Methodologies for indicators monitored by the EA and WFD-UKTAG under the WFD such as macroinvertebrate collection and storage were also followed as specified in guidance and legislation. However, only 6 months of data as opposed to the 12 specified in the WFD was collected due to time restrictions and the necessity to organise access licences. This is a significant limitation as several researchers (e.g. Mattei *et al.,* 2006; Sporka *et al.*, 2006; Wenn, 2008) report an observed degradation in water quality in autumn, which this project was unable to evaluate, and it is therefore possible that status differed for the hydrological year. In addition, several peaks in contaminants were identified in spring throughout this project, most likely caused by stormwater. Although stormwater events were observed in April and May during field visits, this cannot be definitively proven as the catchment was not monitored and hydrograph data was therefore unavailable. Furthermore, 127 samples were collected rather than the 132 expected as some sites were not initially included in the pilot study but were added after initial evaluation.

5.6.2. Laboratory Methodology and Procedures

Prior to any lab procedure, all equipment was calibrated to ensure maximum validity and reliability of the results (refer to Section 3.11). All procedures were thoroughly researched and evaluated in current literature and selected based on suitability. Methodologies for indicators monitored by the WFD-UKTAG under the WFD such as TRP and macroinvertebrate laboratory procedure were followed as specified in guidance and legislation. However, the Phosphomolybdenum blue colorimetric method used was heavily criticised by Goddard *et al.* (2019). It is claimed that the method does not measure all phosphorus in river samples and the use of TRP as the environmental quality standard is claimed to be poorly defined and comprises unknown proportions of extractable particulate phosphorus and soluble reactive phosphorus. This method and the use of Flow Injection Analysis was also found to be flawed during this project. Multiple air pockets formed within the required 400 µl injection tube for the phosphate and ammonia methodologies in contrast to the 20 µl used for the nitrate methodology. This caused several false peaks that required a mitigation of replacement to a 200 µl injection loop and an increased compensatory injection time to twice the required time for 400 µl. The equipment was regularly recalibrated, closely monitored and higher samples were replicated. Furthermore, for the FIA analysis of ammonia, 50% dilution was required for polluted samples as concentrations exceeded detection limits. Finally, it has been suggested that pH is impacted by temperature at a rate of -0.1 unit per 10 °C rise (Morrison et al., 2001). Although all samples were tested at precisely 20°C to maintain uniformity and validity, a fluctuation in pH is likely to have occurred between collection and analysis.

5.6.3. Analysis Methodology

In section 4.2.1, a large increase in species was found over time. However, it is possible that significantly more records exist for the 2000-2019 period as opposed to 1800-1999 due to the increased skill and number of ecologists, the availability of software such as GPS and the increased awareness and monitoring of UK species in the modern day. The reliability of the results is therefore compromised and further research into a modern NFM created from 2020 onwards would carry more validity. Furthermore, more time should have also been allocated to calibration of GIS results as this is a key aspect to ensure the validity of results (Sonnenborg *et al.,* 2017). Although results were calibrated with species subsets and temporal periods, no other catchments could be assessed due to limited time and resources, therefore calibration was not as high a standard as other studies. Therefore, future research must consider this aspect to ensure a more accurate and valid result. Furthermore, although the H’ and J’ indexes are heavily criticised by researchers (e.g. Strong *et al.,* 2017), creating a degree of uncertainty in relation to the H’ and J’ findings of this project, no viable and understandable alterative was available.

5.7. Possibilities for Future Research

This study found high concentrations of toxic pollutants and nutrients such as Cu, Fe, Cd, K, Na and Ca. This reflects the findings of several studies investigating heavy metal and contaminant pollution such as Dawson and Macklin (1998); Scholz (2004); Li and Zhang (2010) and Su *et al.* (2017). In similarity to this project these studies also highlight the necessity for remediation schemes targeted at pollutants such as these but do not offer a solution. However, Basile *et al.* (2012) present an encouraging study focusing on the heavy metal absorption ability of three aquatic macrophytes (*Lemna minor, Elodea canadensis* (invasive to the UK) *and Leptodictyum riparium*). All three were successful in the absorption of Cd, Pb, Zn and Cu, all of which are toxic to aquatic life. Therefore, the use of macrophytes in river management plans is being encouraged. However, only macrophytes native to the subject country should be implemented to maintain natural conditions and avoid ecosystem damage. Furthermore, the improvement and further study of the implementation of all types of NFMs into management plans is urgently needed to understand the true ecological and chemical benefits and this point has also been highlighted by several other studies (e.g. Wenn, 2008; Cashman *et al.,* 2018).

CHAPTER 6. CONCLUSION AND RECOMMENDATIONS

The findings of this study suggest a validated alternate hypothesis in relation to biodiversity (however this could not be statistically tested) as the NFM plantations and artificial ponds improved habitat availability, provided opportunities for floral and faunal species, contained evidence of faunal activity, attracted significantly more individuals after installation and contained diverse populations. However, the correct hypothesis is difficult to determine in relation to water quality as the catchment was severely impacted by nutrient pollution prior to commencement of the project most likely from the WTW point source. However, in 6 months of monitoring, no adverse impact to the water quality of the catchment from the NFM was observed, as no statistically significant concentrations of any pollutants/sediments were discharged from the NFM into the river at any point, suggesting the plantation was successful in retaining/filtering pollutants. Water quality also significantly improved as it flowed through the NFM and for many indicators WD classified as high quality and was of a significantly higher quality than all other sites. An improvement in some parameters was also observed over time, however, this could not be statistically tested and no improvement in the overall quality was identified. Therefore, it is concluded that the NFM was not a significant source of pollution and has potential to improve catchment quality with the addition of a WTW remediation scheme. Due to limitations in time and resources, the observed improvements in the water quality of the catchment could not be definitively proved as it is likely that final classifications for the year were altered and further variation was seen in other seasons. Therefore, long-term monitoring of consistent sites over a several years is required to provide absolute empirical evidence of a positive impact. It is also possible that eutrophication and pollution in the Arrow disguised potential negative impacts of the NFM. Although this is unlikely as the NFM predominantly discharged high quality water, it is possible that a slight influx of pollutants to a sensitive and higher quality river may have a slight impact. Furthermore, with changes in climate, it is possible that the NFMs performance may differ in the more severe seasons predicted in the future. Finally, strategies such as NFM should be used in conjunction with other factors and measures for true success. Therefore, a detailed long-term analysis of the river catchment, its environmental conditions and ecological cost-benefits is required to fully understand the ecological implications of NFM. The following recommendations are therefore made:

- Research including a complete hydrological year to highlight seasonal fluctuation and comply with WFD-UKTAG standards under the WFD based on annual data.
- Long-term and detailed monitoring of various NFM strategies and environmental conditions both pre and post installation to fully assess the success and potential of NFM schemes.
- Further scientific research focused on the ecological potential of NFMs and the potential for catchment water quality improvement.
- Research of an NFM influenced only by diffuse sources of pollution to investigate the true potential unaffected by WTW discharges.
- Further research into appropriate replacements of criticised methodologies, such the Phosphomolybdenum blue colorimetric method, TRP standards and diversity indices.

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APPENDIX A. Ethical Documentation

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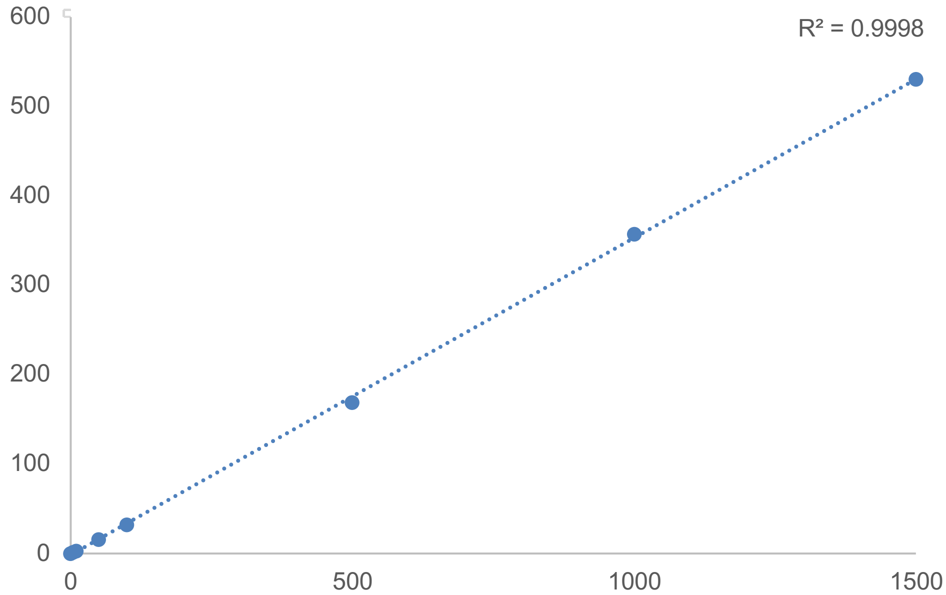
APPENDIX B. Polynomial Regression Charts and Calibrations

Phosphate Calibrations - Flow Injection Analysis - (SOFIA FIASTAR 5000, Foss, Höganäs, Sweden)

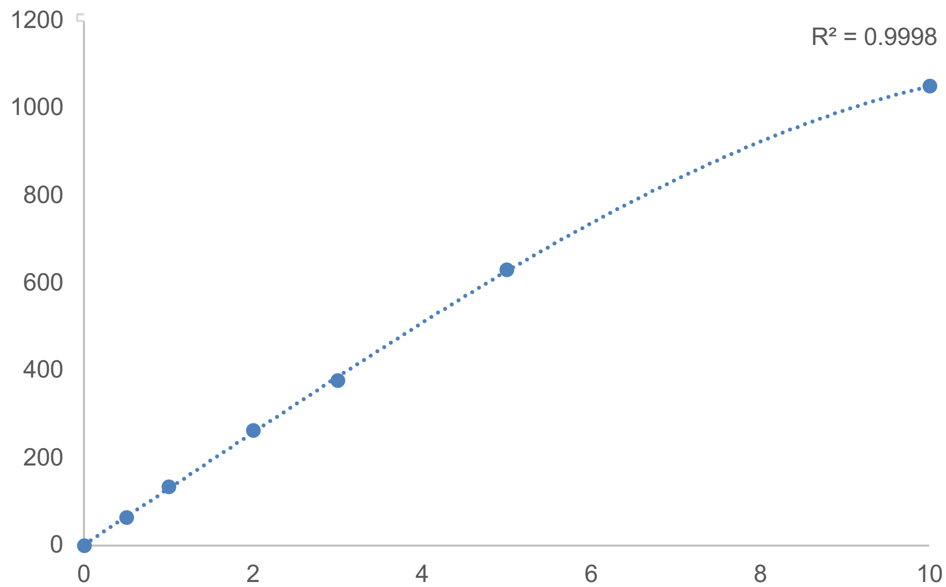
<u>Linear Calibration – Phosphate (PO_4) 0.005 – 5mg/l</u>

Standard (mg/l)	Peak Height (mAU)
0	0.136
5	1.828
10	3.188
50	15.946
100	32.499
500	169.269
1000	356.902



<u>Non-Linear Calibration (3rd Order Polynomial Regression) – Phosphate (PO_4) 0.1 – 10mg/l</u>

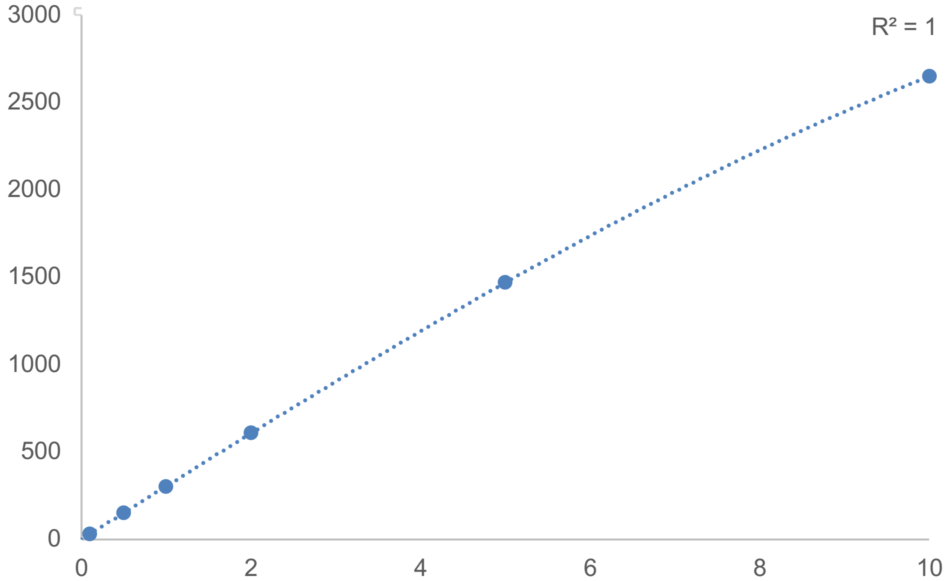
Standard (mg/l)	Peak Height (mAU)
0	0.188
0.5	64.633
1	134.683
2	262.829
3	377.458
5	630.407
10	1050.784



Nitrate Calibrations - Flow Injection Analysis - (SOFIA FIASTAR 5000, Foss, Höganäs, Sweden)

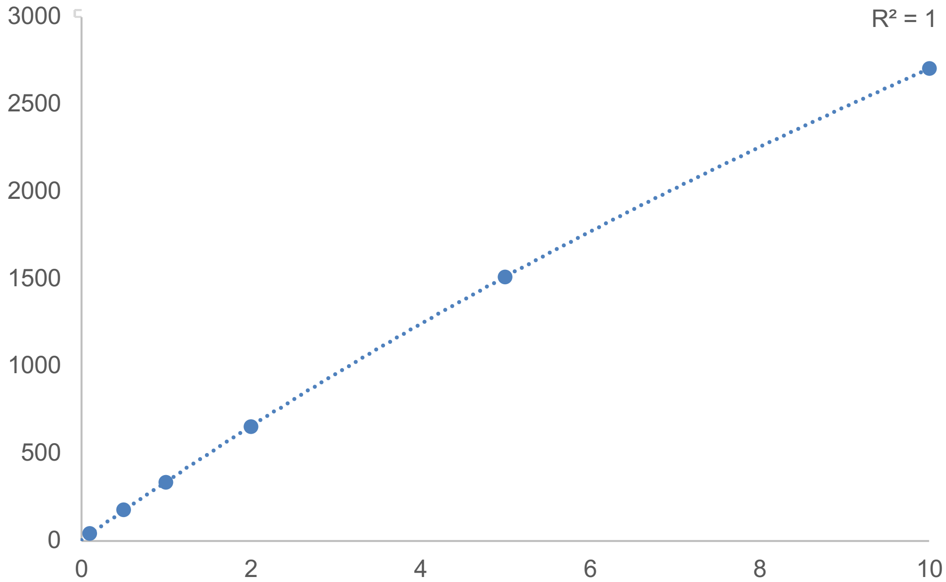
Non-Linear Calibration (3rd Order Polynomial Regression) – Nitrate 0.1 – 10mg/l (NO_2^-/NO_3^-) (Undiluted)

Standard (mg/l)	Peak Height (mAU)
0	-0.218
0.1	33.409
0.5	151.301
1	301.762
2	610.464
5	1469.296
10	2647.69



Non-Linear Calibration (3rd Order Polynomial Regression) – Nitrate (NO_2^-/NO_3^-) 0.1 – 10mg/l (diluted)

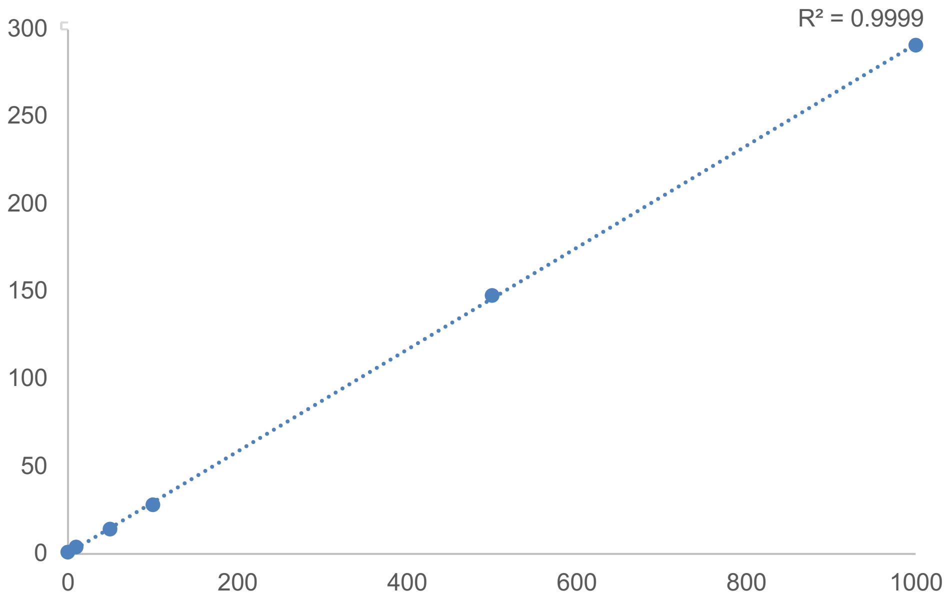
Standard (mg/l)	Peak Height (mAU)
0	-0.125
0.1	42.781
0.5	179.08
1	338.418
2	656.258
5	1513.802
10	2704.875



Ammonia Calibrations - Flow Injection Analysis - (SOFIA FIASTAR 5000, Foss, Höganäs, Sweden)

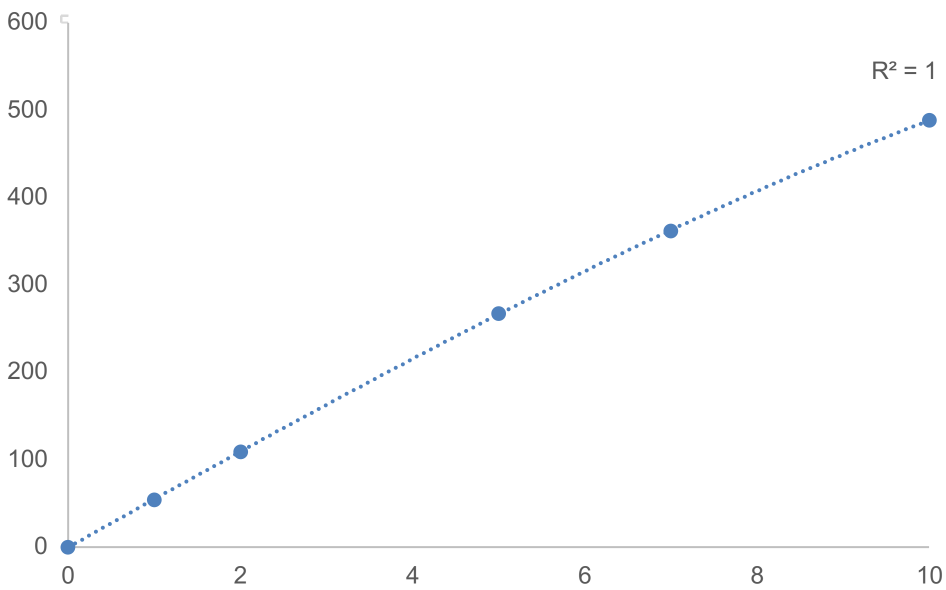
Linear Calibration – Ammonium (NH_4) 0.01 – 1mg/l

Standard (mg/l)	Peak Height (mAU)
0	0.841
10	3.875
50	14.21
100	27.968
500	147.652
1000	291.025

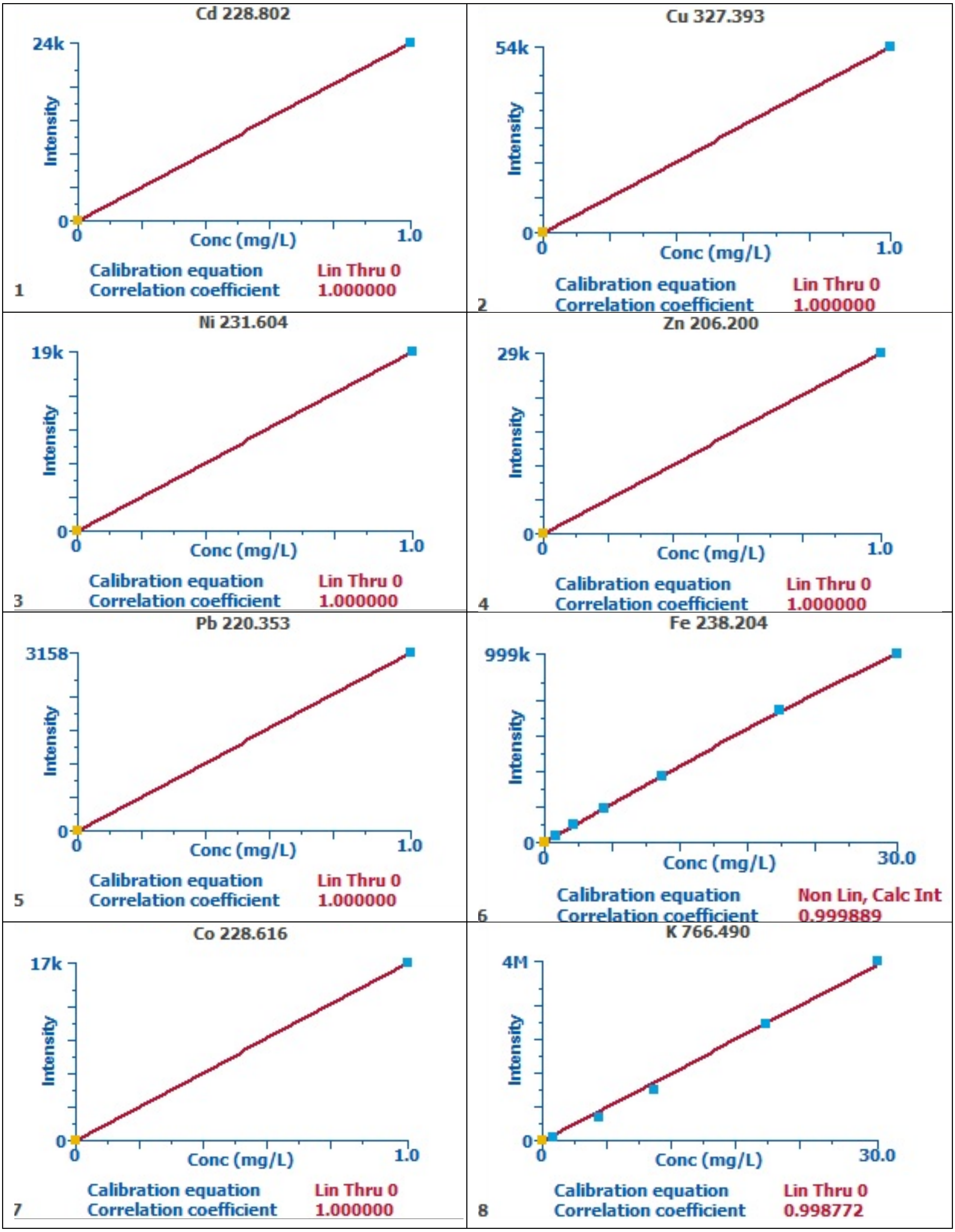


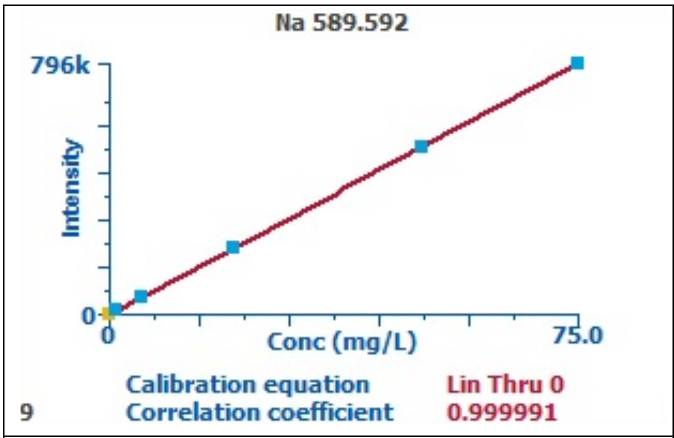
Non-Linear Calibration Curve (3rd Order Polynomial Regression) – Ammonium (NH_4) 1 – 10mg/l

Standard (mg/l)	Peak Height (mAU)
0	0.327
1	54.011
2	109.27
5	267.309
7	361.906
10	488.379



Specific Pollutants/Priority Substances Calibrations – (ICP-OES Optima 8300, Perkin Elmer, Massachusetts, USA).

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Calibration equation
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Correlation coefficient
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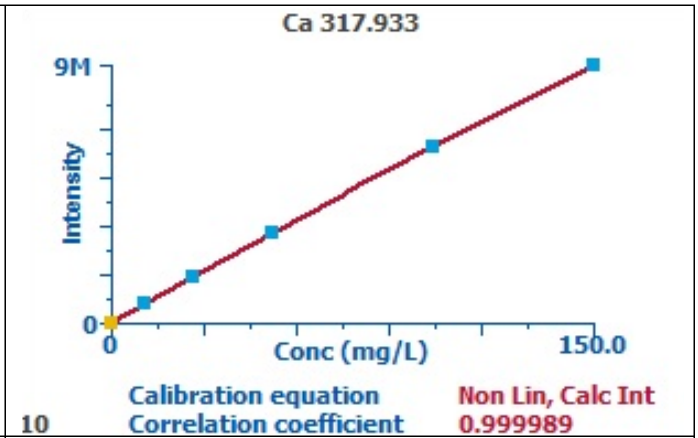
9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Non Lin, Calc Int
Correlation coefficient
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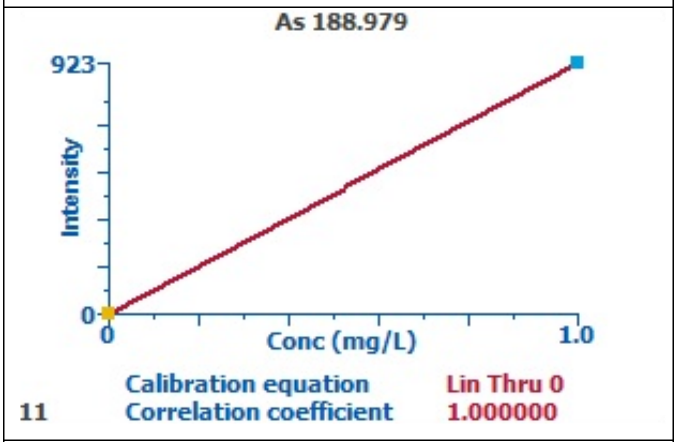
10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Correlation coefficient
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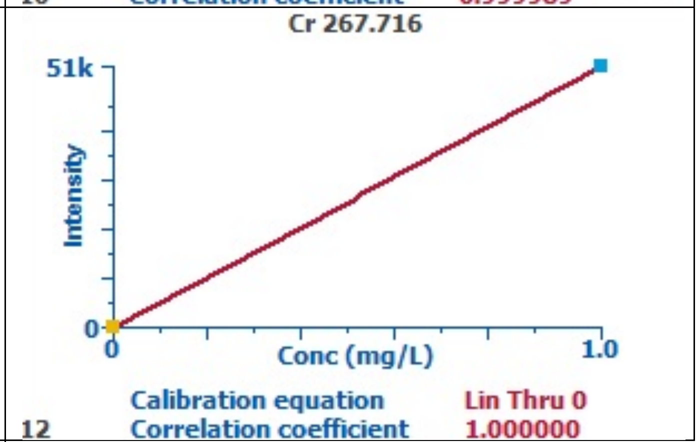
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Correlation coefficient
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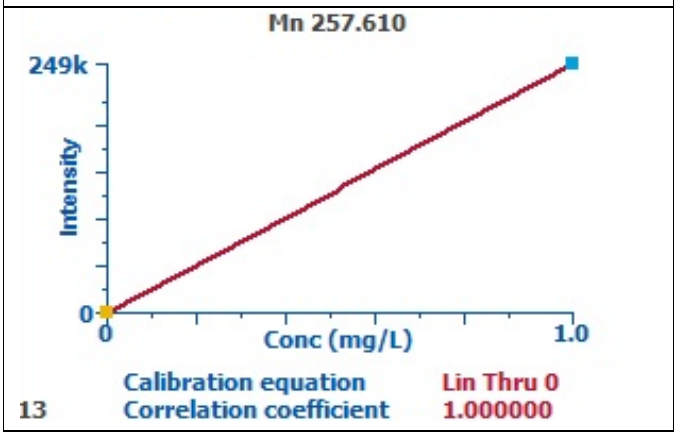
12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Correlation coefficient
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13

APPENDIX C. Summary of Species Records Across the Catchment

Species	Number of Records	Total Population	Date Range	SPI	UK BAP	Local BAP	Legislation
Mammals							
Brown long-eared bat (*Plecotus auratus*)	4	4	2006 - 2016	✓	✓	✓	ECH 4, WCA 5, WCA 6
Noctule (*Nyctalus noctule)*	1	1	2006	✓	✓	✓	ECH 4, WCA 5, WCA 6
Soprano pipistrelle (*Pipistrellus pygmaeus)*	3	192	2006 - 2018	✓	✓	✓	ECH 4, WCA 5, WCA 6
Common pipistrelle (*Pipistrellus pipistrellus)*	10	731	2015 - 2018	-	✓	✓	ECH 4, WCA 5, WCA 6
Brown hare *(Lepus europeaus)*	27	44	1982 - 2017	✓	✓	-	-
Hazel dormouse *Muscardinus avellanarius*	8	19	2012 - 2015	✓	✓	✓	ECH 4, WCA 5, WCA 6
Otter (*Lutra lutra)*	1	1	2016	✓	✓	✓	ECH 2, ECH 4, WCA 5, WCA 6
Birds							
Barn owl *Tyto alba*	6	6	2005 - 2016	-	✓	✓	WCA1i
Kingfisher *(Alcedo atthis)*	1	1	1981	-	-	-	WCA1i
Redwing *(Turdus iliacus)*	1	222	2008	-	-	-	WCA 1i
Amphibians							
Common toad *(Bufo bufo)*	1	1	2018	✓	✓	-	WCA 5 S9(5)
Great crested newt (*Triturus cristatus)*	1	1	1986	✓	✓	✓	ECH 2, ECH 4, WCA 5

SPI: Species of Principal Importance

UK BAP: UK Biological Action Plan

Local BAP: Warwickshire, Coventry and Solihull Local Biological Action Plan

ECH 2: Annex II of the European Communities Council Directive on the Conservation of Natural Habitats and Wild Fauna and Flora. Animal and plant species of community interest whose conservation requires the designation of Special Areas of Conservation.

ECH 4: Annex IV of the European Communities Council Directive on the Conservation of Natural Habitats and Wild Fauna and Flora. Animal and plant species of community interest in need of strict protection.

WCA 1i: Schedule 1 Part 1 of Wildlife and Countryside Act 1981 (as amended). Birds protected by special penalties at all times.

WCA 5: Schedule 5 of Wildlife and Countryside Act 1981 (as amended). Protected animals (other than birds).

WCA 5 S9(5): Schedule 5 Section 9(5) of Wildlife and Countryside Act 1981 (as amended). Protected animals (other than birds). Protection limited to selling, offering for sale, processing or transporting for purpose of sale, or advertising for sale, any live or dead animal, or any part of, or anything derived from, such animal.

WCA 6: Schedule 6 of Wildlife and Countryside Act 1981 (as amended). Animals which may not be killed or taken by certain methods.

Other Records

A large number of other species of common notable birds such as Mistle Thrush (*Turdus viscivorus*), Yellowhammer (*Emberiza citronella*) and House Sparrow (*Passer domesticus*) were present across the catchment. Large numbers of invertebrate species such as moths (e.g. Double Dart (*Graphiphora augur*) and Small Phoenix (*Ecliptopera silaceata*)) and butterflies (e.g. Purple Emperor (*Apatura iris*) and White-Letter Hairstreak (*Satyrium w-album*)) were also noted. Finally, higher/lower flora noted in the catchment included Corn Buttercup (*Ranunculus arvensis*) and Greater-Butterfly Orchid (*Platanthera chlorantha*).

APPENDIX D. Full Botanical Survey Results and Analysis

Studley (ST)

Species (Common Name)	Species (Latin Name)	Sample 1	Sample 2	Sample 3	Total No of Individuals	Shannon Wiener Equation
Sedge	*Carex* sp.	3	0	0	3	-0.16
Common Nettle	*Urtica dioica*	6	1	0	7	-0.27
Cow Parsley	*Anthriscus sylvestris*	1	0	0	1	-0.08
Ground Ivy	*Glechoma hederacea*	2	1	0	3	-0.16
Ivy	*Hedera helix*	1	1	0	2	-0.13
Foxglove	*Digitalis lutea*	1	0	0	1	-0.08
Wood Avens	*Geum urbanum*	0	1	0	1	-0.08
Wood Melick	*Melica uniflora*	0	9	3	12	-0.34
Red Campion	*Silene dioica*	0	0	1	1	-0.08
Cleavers	*Galium aparine*	0	0	10	10	-0.32
Broad-leaved Dock	*Rumex obtusifolius*	0	0	2	2	-0.13
Himalayan Balsam	*Impatiens glandulifera*	0	0	8	8	-0.29
Bramble	*Rubus fruticosus* agg.	0	0	1	1	-0.08
TOTALS	**13 Species**	14	13	25	**52**	**H': 2.17**
						E: 0.85

Water Treatment Works (WTW)

Species (Common Name)	Species (Latin Name)	Sample 1	Sample 2	Sample 3	Total No of Individuals	Shannon Wiener Equation
Common Nettle	*Urtica dioica*	30	10	12	52	-0.35
Bramble	*Rubus fruticosus* agg.	2	0	0	2	-0.08
Cow Parsley	*Anthriscus sylvestris*	1	5	1	7	-0.18
Hedge Woundwort	*Stachys sylvatica*	10	0	0	10	-0.23
Cleavers	*Galium aparine*	5	0	6	11	-0.24
Wavy-Hair Grass	*Deschampsia flexuosa*	4	0	0	4	-0.13
Ground Ivy	*Glechoma hederacea*	0	3	3	6	-0.16
White Dead-Nettle	*Lamium album*	0	1	0	1	-0.04
Broad-leaved Willowherb	*Epilobium montanum*	0	10	0	10	-0.23
Himalayan Balsam	*Impatiens glandulifera*	0	1	0	1	-0.04
Common Nettle	*Urtica dioica*	30	10	12	52	-0.35
TOTALS	**10 Species**	52	30	22	**104**	**H': 1.67**
						E: 0.73

Natural Flood Management Discharge Point (NFM DP)

Species (Common Name)	Species (Latin Name)	Sample 1	Sample 2	Sample 3	Total No of Individuals	Shannon Wiener Equation
Common Nettle	*Urtica dioica*	20	11	11	42	-0.30
Cleavers	*Galium aparine*	5	2	2	9	-0.27
Red Dead-Nettle	*Lamium purpureum*	1	1	0	2	-0.10
Ground Ivy	*Glechoma hederacea*	0	1	1	2	-0.10
White Dead-Nettle	*Lamium album*	0	0	1	1	-0.06
Common Reed	*Phragmites australis*	0	0	13	13	-0.31
Common Nettle	*Urtica dioica*	20	11	11	42	-0.30
Cleavers	*Galium aparine*	5	2	2	9	-0.27
Red Dead-Nettle	*Lamium purpureum*	1	1	0	2	-0.10
TOTALS	**6 Species**	26	15	28	**69**	**H': 1.15**
						E: 0.64

Coughton Court (CC)

Species (Common Name)	Species (Latin Name)	Sample 1	Sample 2	Sample 3	Total No of Individuals	Shannon Wiener Equation
Yorkshire-Fog	*Holcus lanatus*	20	0	5	25	-0.37
Common Nettle	*Urtica dioica*	4	1	12	17	-0.35
White Dead-Nettle	*Lamium album*	1	0	1	2	-0.11
Cleavers	*Galium aparine*	2	0	1	3	-0.14
Hedge Bindweed	*Calystegia sepium*	0	3	0	3	-0.14
Himalayan Balsam	*Impatiens glandulifera*	0	1	3	4	-0.17
Hogweed	*Heracleum sphondylium*	0	1	0	1	-0.06
Wavy-Hair Grass	*Deschampsia flexuosa*	0	0	10	10	-0.29
TOTALS	**8 Species**	27	6	32	**65**	**H': 1.63**
						E: 0.78

Ford (FD)

Species (Common Name)	Species (Latin Name)	Sample 1	Sample 2	Sample 3	Total No of Individuals	Shannon Wiener Equation
Reed Canary-Grass	*Phalaris arundinacea*	24	2	0	26	-0.36
Creeping Buttercup	*Ranunculus repens*	20	0	0	20	-0.33
Sweet Vernal-Grass	*Anthoxanthum odoratum*	10	0	5	15	-0.30
Great Willowherb	*Epilobium hirsutum*	0	5	0	5	-0.16
Ground Ivy	*Glechoma hederacea*	0	0	1	1	-0.05
Meadow Buttercup	*Ranunculus acris*	0	0	25	25	-0.35
TOTALS	**6 Species**	54	7	31	92	**H': 1.55**
						E: 0.86

Kings Coughton (KC)

Species (Common Name)	Species (Latin Name)	Sample 1	Sample 2	Sample 3	Total No of Individuals	Shannon Wiener Equation
Bramble	*Rubus fruticosus* agg.	1	1	0	2	-0.11
White Dead-Nettle	*Lamium album*	1	0	0	1	-0.07
Mugwort	*Artemisia vulgaris*	6	0	0	6	-0.23
Hedge Woundwort	*Stachys sylvatica*	1	1	1	3	-0.15
Ground Ivy	*Glechoma hederacea*	1	1	1	3	-0.15
Hedgerow Crane's-Bill	*Geranium pyrenaicum*	1	0	0	1	-0.07
Dog-rose	*Rosa canina*	0	1	0	1	-0.07
Red Campion	*Silene dioica*	0	1	0	1	-0.07
Wood Avens	*Geum urbanum*	0	6	0	6	-0.23
Cleavers	*Galium aparine*	0	2	1	3	-0.15
Cow Parsley	*Anthriscus sylvestris*	0	5	1	6	-0.23
Hedge Bindweed	*Calystegia sepium*	0	1	1	2	-0.11
Dandelion	*Taraxacum officinale* agg.	0	1	0	1	-0.07
Common Nettle	*Urtica dioica*	0	10	0	10	-0.30
Borage	*Borago officinalis*	0	1	0	1	-0.07
Sedge	*Carex* sp.	0	0	3	3	-0.15
Himalayan Balsam	*Impatiens glandulifera*	0	0	5	5	-0.21
Meadow Buttercup	*Ranunculus acris*	0	0	3	3	-0.15
Hogweed	*Heracleum sphondylium*	0	0	0	1	1
TOTALS	**19 Species**	11	31	17	59	**H': 2.68**
						E: 0.91

Eastern Extent of the Main Drainage Channel (ED)

Species (Common Name)	Species (Latin Name)	Sample 1	Sample 2	Sample 3	Total No of Individuals	Shannon Wiener Equation
Yorkshire-Fog	*Holcus lanatus*	20	25	0	45	-0.35
Cleavers	*Galium aparine*	5	1	0	6	-0.18
Broad-leaved Dock	*Rumex obtusifolius*	3	0	0	3	-0.11
Marsh-Bedstraw	*Galium palustre*	2	0	0	2	-0.08
Common Nettle	*Urtica dioica*	4	3	7	14	-0.29
Bramble	*Rubus fruticosus* agg.	1	1	2	4	-0.14
Hedge Woundwort	*Stachys sylvatica*	1	0	0	1	-0.05
Ground Ivy	*Glechoma hederacea*	0	5	0	5	-0.16
Yarrow	*Achillea millefolium*	0	1	0	1	-0.05
Crested Dog's-Tail	*Cynosurus cristatus*	0	0	10	10	-0.24
TOTALS	**10 Species**	36	36	19	91	**H': 1.65**
						E: 0.72

Central Extent of the Main Drainage Channel (CD)

Species (Common Name)	Species (Latin Name)	Sample 1	Sample 2	Sample 3	Total No of Individuals	Shannon Wiener Equation
Crested Dog's-Tail	*Cynosurus cristatus*	3	0	0	3	-0.09
Common Nettle	*Urtica dioica*	40	10	2	52	-0.37
Cleavers	*Galium aparine*	10	0	0	10	-0.20
Ground Ivy	*Glechoma hederacea*	4	0	0	4	-0.11
Bramble	*Rubus fruticosus* agg.	0	2	0	2	-0.07
Greater Burdock	*Arctium lappa*	0	4	0	4	-0.11
Broad-leaved Dock	*Rumex obtusifolius*	0	2	4	6	-0.14
Sweet Vernal-Grass	*Anthoxanthum odoratum*	0	2	5	7	-0.16
Wavy Hair-Grass	*Deschampsia flexuosa*	0	7	0	7	-0.16
Branched Horsetail	*Equisetum ramosissimum*	0	10	8	18	-0.28
Hedge Woundwort	*Stachys sylvatica*	0	5	0	5	-0.13
Meadowsweet	*Filipendula ulmaria*	0	0	8	8	-0.18
TOTALS	**12 Species**	57	42	27	126	**H': 1.99**
						E: 0.80

Western Extent of the Main Drainage Channel (WD)

Species (Common Name)	Species (Latin Name)	Sample 1	Sample 2	Sample 3	Total No of Individuals	Shannon Wiener Equation
Common Nettle	*Urtica dioica*	15	15	0	30	-0.37
Red Campion	*Silene dioica*	2	0	0	2	-0.09
Cleavers	*Galium aparine*	20	15	1	36	-0.37
Tufted Hair Grass	*Deschampsia cespitosa*	10	0	0	10	-0.25
Meadowsweet	*Filipendula ulmaria*	0	0	5	5	-0.16
Bramble	*Rubus fruticosus* agg.	0	0	1	1	-0.05
Great Willowherb	*Epilobium hirsutum*	0	0	4	4	-0.14
TOTALS	**7 Species**	47	30	11	88	**H': 1.42**
						E: 0.73

Pond 1 (P1)

Species (Common Name)	Species (Latin Name)	Sample 1	Sample 2	Sample 3	Total No of Individuals	Shannon Wiener Equation
Common Reed	*Phragmites australis*	23	0	0	23	-0.34
Greater Plantain	*Plantago major*	1	0	0	1	-0.05
Creeping Buttercup	*Ranunculus repens*	2	0	0	2	-0.08
Broad-leaved Willowherb	*Epilobium montanum*	2	0	0	2	-0.08
Small Fleabane	*Pulicaria vulgaris*	8	0	0	8	-0.21
Soft-Rush	*Juncus effusus*	0	20	30	50	-0.34
Wavy Hair-Grass	*Deschampsia flexuosa*	0	2	0	2	-0.08
Oxeye Daisy	*Leucanthemum vulgare*	0	1	0	1	-0.05
Creeping-Jenny	*Lysimachia nummularia*	0	1	1	2	-0.08
Yorkshire-Fog	*Holcus lanatus*	0	0	5	5	-0.15
TOTALS	**10 Species**	36	24	36	96	**H': 1.46**
						E: 0.64

Pond 2 (P2)

Species (Common Name)	Species (Latin Name)	Sample 1	Sample 2	Sample 3	Total No of Individuals	Shannon Wiener Equation
Soft-Rush	*Juncus effusus*	2	3	5	10	-0.27
Selfheal	*Prunella vulgaris*	5	0	0	5	-0.18
Ribwort Plantain	*Plantago lanceolata*	1	1	0	2	-0.10
Creeping Buttercup	*Ranunculus repens*	2	0	0	2	-0.10
Great Willowherb	*Epilobium hirsutum*	2	4	0	6	-0.20
Meadow Vetchling	*Lathyrus pratensis*	2	0	0	2	-0.10
Wavy Hair-Grass	*Deschampsia flexuosa*	10	10	0	20	-0.35
Lesser Centuary	*Centaurium pulchellum*	2	0	0	2	-0.10
Common Mouse-Ear	*Cerastium fontanum*	1	0	0	1	-0.06
Ash	*Fraxinus excelsior*	0	3	0	3	-0.13
Yorkshire-Fog	*Holcus lanatus*	0	10	0	10	-0.27
Hedge Bedstraw	*Galium mollugo*	0	0	10	10	-0.27
Marsh Woundwort	*Stachys palustris*	0	0	3	3	-0.13
TOTALS	**13 Species**	27	31	18	76	**H': 2.23**
						E: 0.87

APPENDIX E. Full Macroinvertebrate Survey Results and Analysis

Macroinvertebrate WHPT NTAXA, WHPT ASPT, H' and J'. H' and J' calculations include non-scoring WHPT / BMWP only taxa.

SPRING - 17th April 2019

Class / Order	Family	Ab	WHPT AB Cat Score	Total Ab	WHPT NTAXA	WHPT ASPT	H'	J'
Studley (ST)								
Bivalvia	*Sphaeriidae*	1	4.4	**45**	**11**	**5.25**	**2.15**	**0.90**
Clitellata	*Oligochaeta*	8	3.6					
Crustacea	*Gammaridae*	2	4.2					
Crustacea	*Asellidae*	2	4					
Diptera	*Chironomidae*	7	1.2					
Ephemeroptera	*Baetidae*	6	3.6					
Ephemeroptera	*Caenidae*	1	6.5					
Gastropoda	*Viviparidae*	6	5.2					
Gastropoda	*Ancylidae*	8	5.8					
Trichoptera	*Rhyacophilidae*	3	8.1					
Trichoptera	*Philopotamidae*	1	11.2					
Water Treatment Works (WTW)								
Bivalvia	*Unionidae*	1	5.2	**53**	**8**	**3.53**	**1.68**	**0.81**
Clitellata	*Oligochaeta*	4	3.6					
Clitellata	*Glossiphoniidae*	11	2.5					
Crustacea	*Gammaridae*	2	4.2					
Crustacea	*Asellidae*	19	2.3					
Diptera	*Chironomidae*	11	1.3					
Ephemeroptera	*Baetidae*	4	3.6					
Trichoptera	*Phryganeidae*	1	5.5					
NFM Discharge Point (NFM DP)								
Clitellata	*Oligochaeta*	6	3.6	**127**	**14**	**4.96**	**1.65**	**0.63**
Clitellata	*Glossiphoniidae*	2	3.4					
Clitellata	*Erpobdellidae*	2	3.6					
Crustacea	*Asellidae*	6	4					
Crustacea	*Gammaridae*	1	4.2					
Diptera	*Chironomidae*	50	1.3					
Diptera	*Simulidae*	5	5.5					
Ephemeroptera	*Baetidae*	45	5.9					
Gastropoda	*Viviparidae*	3	5.2					
Gastropoda	*Ancylidae*	2	5.8					
Gastropoda	*Lymnaeidae*	1	3.6					
Gastropoda	*Planorbidae*	1	3.2					
Trichoptera	*Philopotamidae*	2	11.2					
Trichoptera	*Sericostomatidae*	1	8.9					

Class / Order	Family	Ab	WHPT AB Cat Score	Total Ab	WHPT NTAXA	WHPT ASPT	H’	J’
Coughton Court (CC)								
Clitellata	*Glossiphoniidae*	1	3.4	**31**	**9**	**4.38**	**1.91**	**0.87**
Coleoptera	*Gyrinidae*	1	8.1					
Coleoptera	*Dytiscidae*	5	4.5					
Crustacea	*Gammaridae*	8	4.2					
Crustacea	*Asellidae*	2	4					
Diptera	*Chironomidae*	8	1.2					
Diptera	*Simulidae*	3	5.5					
Gastropoda	*Valvatidae*	2	3.3					
Gastropoda	*Viviparidae*	1	5.2					
Ford (F)								
Clitellata	*Oligochaeta*	1	3.6	**34**	**8**	**4.24**	**1.73**	**0.83**
Crustacea	*Asellidae*	5	4					
Crustacea	*Gammaridae*	2	4.2					
Diptera	*Chironomidae*	12	1.3					
Diptera	*Simulidae*	5	5.5					
Ephemeroptera	*Baetidae*	7	3.6					
Ephemeroptera	*Caenidae*	1	6.5					
Gastropoda	*Viviparidae*	1	5.2					
Kings Coughton (KC)								
Clitellata	*Oligochaeta*	4	3.6	**90**	**11**	**5.10**	**1.76**	**0.74**
Crustacea	*Asellidae*	1	4					
Crustacea	*Gammaridae*	1	4.2					
Diptera	*Chironomidae*	12	1.3					
Ephemeroptera	*Baetidae*	21	5.9					
Ephemeroptera	*Caenidae*	1	6.5					
Gastropoda	*Ancylidae*	2	5.8					
Gastropoda	*Lymnaeidae*	4	3.6					
Trichoptera	*Hydropsychidae*	36	7.2					
Trichoptera	*Polycentropididae*	4	8.2					
Trichoptera	*Psychomiidae*	4	5.8					
Eastern Extent of the Main Drainage Channel (ED)								
Crustacea	*Gammaridae*	1	4.2	**8**	**3**	**3.63**	**0.74**	**0.67**
Diptera	*Simulidae*	6	5.5					
Diptera	*Chironomidae*	1	1.2					
Central Extent of the Main Drainage Channel (CD)								
Clitellata	*Oligochaeta*	1	3.6	**14**	**2**	**4.05**	**0.26**	**0.37**
Crustacea	*Gammaridae*	13	4.5					

Class / Order	Family	Ab	WHPT AB Cat Score	Total Ab	WHPT NTAXA	WHPT ASPT	H’	J’
Western Extent of the Main Drainage Channel (WD)								
Crustacea	*Gammaridae*	40	4.5	**76**	**14**	**5.46**	**1.60**	**0.60**
Crustacea	*Asellidae*	2	4					
Crustacea	*Corophiidae*	1	5.7					
Diptera	*Simulidae*	2	5.5					
Diptera	*Chironomidae*	2	1.2					
Ephemeroptera	*Ephemeridae*	18	8.8					
Gastropoda	*Neritidae*	1	6.4					
Gastropoda	*Valvatidae*	2	3.3					
Gastropoda	*Ancylidae*	1	5.8					
Gastropoda	*Physidae*	1	2.7					
Megaloptera	*Sialidae*	2	5.5					
Trichoptera	*Phryganeidae*	1	5.5					
Trichoptera	*Sericostomatidae*	2	8.9					
Trichoptera	*Lepidostomatidae*	1	9.9					
Pond 1 (P1)								
Crustacea	*Gammaridae*	1	4.2	**19**	**6**	**4.30**	**1.31**	**0.73**
Ephemeroptera	*Baetidae*	5	3.6					
Gastropoda	*Viviparidae*	1	5.2					
Hemiptera	*Corixidae*	10	3.9					
Odonata	*Coenagrionidae*	1	3.4					
Trichoptera	*Phryganeidae*	1	5.5					
Pond 2 (P2)								
Gastropoda	*Physidae*	5	2.7	**11**	**4**	**4.68**	**1.24**	**0.89**
Hemiptera	*Notonectidae*	1	3.4					
Hemiptera	*Corixidae*	3	3.7					
Trichoptera	*Sericostomatidae*	2	8.9					

Autumn - 19th – 23rd August 2019

Class / Order	Family	Ab	WHPT AB Cat Score	Total Ab	WHPT NTAXA	WHPT ASPT	H'	J'
Studley (ST)								
Clitellata	*Oligochaeta*	18	2.3	**85**	**11**	**4.40**	**2.20**	**0.89**
Crustacea	*Gammaridae*	8	4.2					
Crustacea	*Asellidae*	3	4					
Diptera	*Tipulidae*	5	5.4					
Diptera	*Chironomidae*	4	1.2					
Ephemeroptera	*Baetidae*	2	3.6					
Gastropoda	*Hydrobiidae*	4	4.1					
Gastropoda	*Physidae*	17	2.7					
Gastropoda	*Viviparidae*	1	5.2					
Trichoptera	*Rhyacophilidae*	11	9.2					
Trichoptera	*Hydropsychidae*	12	7.2					
Water Treatment Works (WTW)								
Clitellata	*Oligochaeta*	15	2.3	**102**	**11**	**4.65**	**1.88**	**0.79**
Clitellata	*Glossiphoniidae*	8	3.4					
Crustacea	*Gammaridae*	4	4.2					
Diptera	*Chironomidae*	26	1.3					
Diptera	*Simulidae*	5	5.5					
Ephemeroptera	*Baetidae*	11	5.9					
Gastropoda	*Physidae*	1	2.7					
Gastropoda	*Valvatidae*	1	3.3					
Gastropoda	*Viviparidae*	1	5.2					
Odonata	*Agriidae*	29	6.2					
Trichoptera	*Philopotamidae*	1	11.2					
NFM Discharge Point (NFM DP)								
Clitellata	*Oligochaeta*	7	3.6	**86 (89)**	**8**	**4.84**	**1.75**	**0.80**
Crustacea	*Gammaridae*	5	4.2					
Diptera	*Chironomidae*	13	1.3					
Ephemeroptera	*Baetidae*	34	5.9					
Ephemeroptera	*Caenidae*	1	6.5					
Gastropoda	*Viviparidae*	2	5.2					
Odonata	*Lestidae*	3	X					
Odonata	*Agriidae*	19	6.2					
Trichoptera	*Hydropsychidae*	5	5.8					

Class / Order	Family	Ab	WHPT AB Cat Score	Total Ab	WHPT NTAXA	WHPT ASPT	H’	J’
Coughton Court (CC)								
Bivalvia	*Unionidae*	2	5.2	**96**	**11**	**4.72**	**1.66**	**0.69**
Clitellata	*Glossiphoniidae*	2	3.4					
Coleoptera	*Haliplidae*	1	3.6					
Crustacea	*Gammaridae*	25	4.5					
Diptera	*Chironomidae*	5	1.2					
Ephemeroptera	*Ephemeridae*	1	8.3					
Ephemeroptera	*Caenidae*	1	6.5					
Ephemeroptera	*Baetidae*	1	3.6					
Gastropoda	*Viviparidae*	20	6.7					
Gastropoda	*Physidae*	3	2.7					
Odonata	*Agriidae*	35	6.2					
Kings Coughton (KC)								
Clitellata	*Oligochaeta*	2	3.6	**99 (98)**	**17**	**5.02**	**2.24**	**0.77**
Clitellata	*Glossiphoniidae*	1	3.4					
Coleoptera	*Haliplidae*	1	3.6					
Crustacea	*Gammaridae*	14	4.5					
Crustacea	*Asellidae*	4	4					
Diptera	*Chironomidae*	16	1.3					
Diptera	*Simulidae*	1	5.5					
Ephemeroptera	*Ephemerellidae*	5	7.9					
Ephemeroptera	*Baetidae*	13	5.9					
Gastropoda	*Physidae*	1	2.7					
Gastropoda	*Hydrobiidae*	1	4.1					
Gastropoda	*Viviparidae*	1	5.2					
Gastropoda	*Ancylidae*	2	5.8					
Hemiptera	*Hydrometridae*	1	4.3					
Odonata	*Lestidae*	1	X					
Trichoptera	*Hydropsychidae*	27	7.2					
Trichoptera	*Polycentropodidae*	7	8.2					
Trichoptera	*Rhyacophilidae*	1	8.1					
Eastern Extent of the Main Drainage Channel (ED)								
Coleoptera	*Elmidae*	1	5.3	**81**	**4**	**4.68**	**0.25**	**0.18**
Crustacea	*Gammaridae*	77	4.5					
Hemiptera	*Mesoveliidae*	1	4.7					
Megaloptera	*Sialidae*	2	5.5					
Central Extent of the Main Drainage Channel (CD)								
Crustacea	*Gammaridae*	44	4.5	**54**	**4**	**4.65**	**0.60**	**0.43**
Diptera	*Chironomidae*	8	1.2					
Hemiptera	*Mesoveliidae*	1	4.7					
Trichoptera	*Polycentropodidae*	1	8.2					

Class / Order	Family	Ab	WHPT AB Cat Score	Total Ab	WHPT NTAXA	WHPT ASPT	H'	J'
Western Extent of the Main Drainage Channel (WD)								
Clitellata	*Glossiphoniidae*	1	3.4	**66**	**8**	**5.26**	**1.20**	**0.58**
Crustacea	*Gammaridae*	44	4.5					
Crustacea	*Asellidae*	1	4					
Diptera	*Pediciidae*	6	5.4					
Diptera	*Chironomidae*	3	1.2					
Diptera	*Ptychopteridae*	1	6.4					
Ephemeroptera	*Ephemeridae*	7	8.3					
Trichoptera	*Sericostomatidae*	3	8.9					
Pond 1 (P1)								
Clitellata	*Oligochaeta*	1	3.6	**112**	**10**	**3.70**	**1.70**	**0.74**
Clitellata	*Glossiphoniidae*	1	3.4					
Coleoptera	*Dytiscidae*	12	4.8					
Crustacea	*Gammaridae*	30	4.5					
Diptera	*Chironomidae*	2	1.2					
Ephemeroptera	*Baetidae*	18	5.9					
Gastropoda	*Physidae*	38	2.7					
Hemiptera	*Pleidae*	7	3.3					
Megaloptera	*Sialidae*	1	5.5					
Odonata	*Libellulidae*	2	4.1					
Pond 2 (P2)								
Clitellata	*Glossiphoniidae*	1	3.4	**56 (55)**	**9**	**3.64**	**1.80**	**0.78**
Crustacea	*Gammaridae*	6	4.2					
Diptera	*Chironomidae*	2	1.2					
Ephemeroptera	*Baetidae*	22	5.9					
Gastropoda	*Physidae*	9	2.7					
Hemiptera	*Notonectidae*	3	3.4					
Hemiptera	*Corixidae*	9	3.7					
Megaloptera	*Sialidae*	1	5.5					
Odonata	*Libelluiidae*	2	4.1					
Odonata	*Lestidae*	1	X					

APPENDIX F. Monthly Average Graph Values for Physico-Chemical Indicators

Dissolved Oxygen (% Saturation)

Site	March	April	May	June	July	August
ST	143	130	136	98	122	108
WTW	98	97	85	95	98	95
NFM DP	88	82	94	107	108	99
CC	100	77	91	108	113	94
FD	108	87	96	105	116	/
KC	100	96	93	111	112	91
ED	88	104	65	110	45	59
CD	90	93	97	89	95	93
WD	92	96	101	98	110	92
P1	90	86	116	119	104	83
P2	62	85	102	88	88	70

Biochemical Oxygen Demand (mg/l)

Site	March	April	May	June	July	August
ST	0.9	0.5	1.7	0.5	0.9	1.9
WTW	1.0	2.8	4.4	1.7	2.4	1.0
NFM DP	2.0	3.3	5.6	1.6	2.0	1.8
CC	3.0	2.5	1.2	2.7	1.2	1.4
FD	1.7	4.4	2.0	1.7	1.5	/
KC	2.0	2.2	4.5	1.1	1.4	1.6
ED	0.8	1.1	3.3	0.5	6.8	0.6
CD	0.6	0.5	1.2	0.9	0.6	0.3
WD	1.1	2.6	3.6	0.5	1.3	1.1
P1	2.5	0.6	2.0	1.2	1.4	0.8
P2	1.3	4.6	1.2	1.4	1.5	1.1

Total Reactive Phosphorus (µg/l)

Site	March	April	May	June	July	August
ST	113	188	280	264	375	284
WTW	460	718	644	372	627	810
NFM DP	464	542	714	282	659	721
CC	331	523	619	298	583	535
FD	353	502	672	212	510	/
KC	451	454	698	261	569	608
ED	519	408	769	668	293	409
CD	87	46	103	227	141	180
WD	25	40	88	204	166	162
P1	53	41	33	162	280	83
P2	165	255	49	256	261	150

Total Nitrate (mg/l)

Site	March	April	May	June	July	August
ST	3.8	3.8	3.2	3.7	3.3	3.2
WTW	10.7	15.2	15.6	16.4	15.1	16.4
NFM DP	11.4	13.9	14.1	11.6	15.4	14.0
CC	7.9	12.3	11.4	13.3	11.9	12.1
FD	8.9	11.0	11.3	8.7	11.5	/
KC	8.6	12.1	17.3	8.3	14.3	12.3
ED	0.7	0.5	0.1	0.8	1.5	0.5
CD	2.4	3.0	2.4	1.7	3.3	3.1
WD	2.8	3.3	3.4	2.5	3.4	3.0
P1	0.2	0.1	0.0	0.2	0.1	0.2
P2	1.2	1.3	0.2	0.3	0.1	0.1

Total Ammonia (mg/l)

Site	March	April	May	June	July	August
ST	0.0	0.0	0.0	0.2	0.1	0.1
WTW	0.2	1.9	1.6	0.4	0.6	0.6
NFM DP	0.1	1.4	1.6	0.2	0.3	0.3
CC	0.1	1.7	1.2	0.3	0.1	0.3
FD	0.1	1.7	0.9	0.3	0.1	/
KC	0.0	0.4	0.3	0.2	0.2	0.4
ED	0.0	0.0	0.2	0.1	0.2	0.2
CD	0.0	0.0	0.0	0.1	0.1	0.1
WD	0.0	0.0	0.2	0.2	0.2	0.2
P1	0.1	0.1	0.0	0.1	0.1	0.3
P2	0.1	0.1	0.1	0.3	0.2	0.3

Suspended Solids (mg/l)

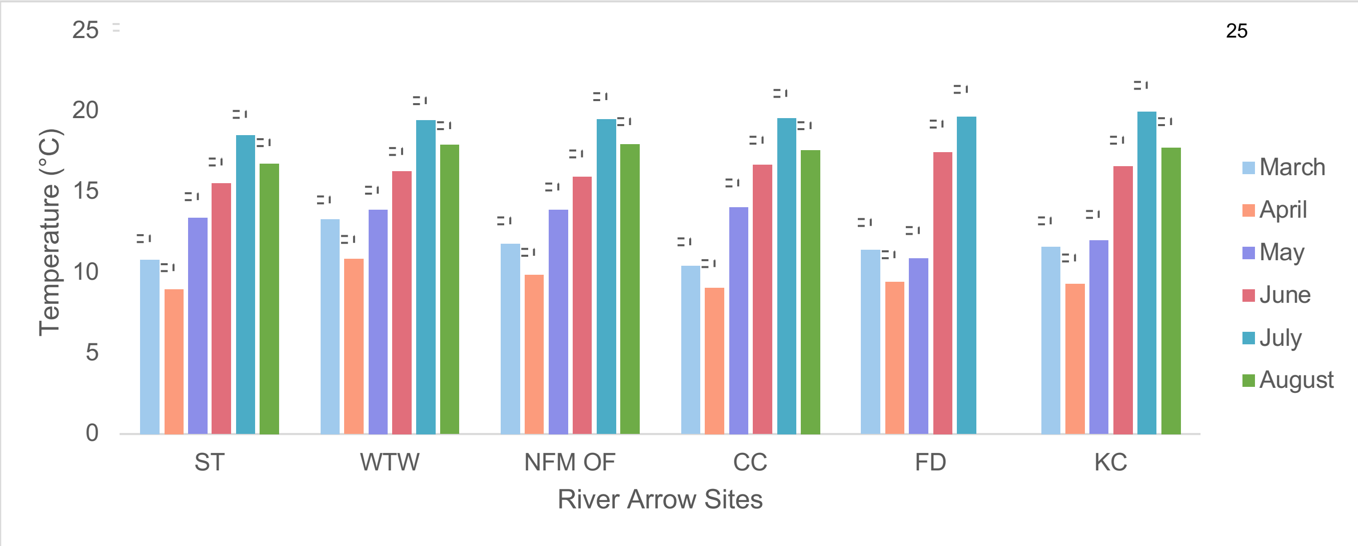
Site	March	April	May	June	July	August
ST	0.4	5	7.4	2.6	2.7	3.3
WTW	1	10.1	5.2	6.8	6.1	4.4
NFM DP	4.1	8.1	20.8	12.8	4.1	3.5
CC	5.1	7.1	21.3	5.1	2.1	2.3
FD	1	8.4	21.6	11.6	5	/
KC	1.6	7.1	12	5.8	4.1	2.4
ED	58	147	56	36.9	11.2	7.2
CD	29.5	38.6	87.8	89	36.6	20.2
WD	54.8	16.7	9.6	23	11.7	11.3
P1	16.6	22.6	21.2	8.9	14	25.6
P2	106.8	72.9	58.5	33.8	28	42

Temperature (°C)

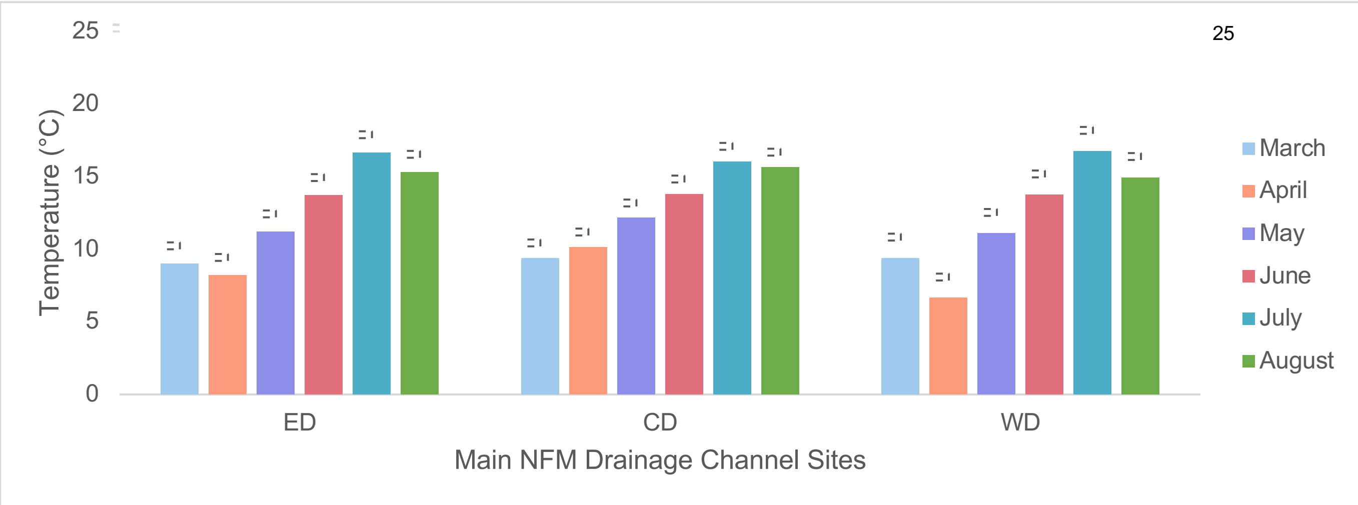
Site	March	April	May	June	July	August
ST	10.8	9.0	13.4	15.6	18.5	16.8
WTW	13.3	10.9	13.9	16.3	19.5	17.9
NFM DP	11.8	9.9	13.9	16.0	19.5	18.0
CC	10.4	9.1	14.1	16.7	19.6	17.6
FD	11.4	9.4	10.9	17.5	19.7	/
KC	11.6	9.3	12.0	16.6	20.0	17.8
ED	9.0	8.2	11.2	13.7	16.7	15.3
CD	9.4	10.2	12.2	13.8	16.1	15.7
WD	9.4	6.7	11.1	13.8	16.8	15.0
P1	12.7	9.8	16.8	20.0	22.9	20.4
P2	12.3	9.8	16.0	19.5	23.3	20.7

APPENDIX G. Temperature Data Summary

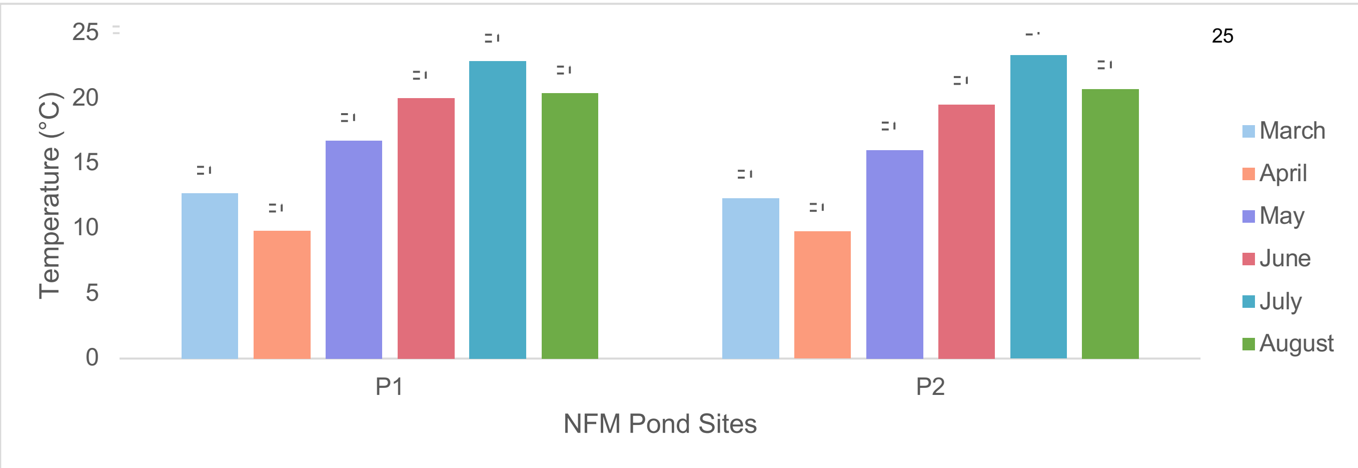
Average monthly temperature (ºC) of the River Arrow over 6 months (+/- 1 SE).



Average monthly temperature (ºC) of the main NFM drainage channel over 6 months (+/- 1 SE).



Average monthly temperature (ºC) of the NFM ponds over 6 months (+/- 1 SE).



Significant Differences Between Sites

Kruskal-Wallis/Mann-Whitney-U (ponds) results (temperature) – within waterbodies.

Location	P-Value
River Arrow	0.966
Drainage Channel	0.877
Ponds	0.847

Kruskal-Wallis results (temperature) – between waterbodies.

Location		P-Value
Overall Catchment		<0.001***
Post-Hoc Multiple Comparisons		
River Arrow	Drainage Channel	0.045*
	Ponds	0.065
Drainage Channel	Ponds	<0.001***

Spatial and Seasonal Variation Across the Catchment

6-month summary of the variation in temperature across individual sites.

Test	ST	WTW	NFM DP	CC	FD	KC	ED	CD	WD	P1	P2
Mean	14.29	15.46	15.10	14.95	14.03	14.81	12.65	13.18	12.35	17.48	17.35
SD	3.80	3.47	3.85	4.27	0.14	4.72	3.52	2.68	3.89	5.19	5.42
Status	H	H	H	H	H	H	H	H	H	H	H
Seasonal Variation – Mann-Whitney U											
Spring	11.1	12.6	11.9	11.3	10.4	10.8	9.6	10.8	9.0	13.2	12.8
Summer	16.9	17.9	17.8	18	18.6	18.1	15.2	15.2	15.2	21.1	21.2
P-Value	0.013*	0.009**	0.006**	0.017**	0.016**	0.017**	0.009**	0.009**	0.009**	0.03*	0.03*

6-month summary of the variation in temperature across the catchment.

Test	River Arrow	Drainage Channel	Ponds
Mean	14.8	12.72	17.4
SD	3.99	3.31	5.18
Status	H	H	H

Temporal Variation

2019 temperature status and official historical catchment status classifications.

Waterbody	6-Month Status	Past EA Catchment Status Classifications for temperature – Arrow*
River Arrow	High	High (Cycles 1&2)
Main NFM Drainage Channel	High	
Pond	High	
*Official EA catchment status classifications only include the main River Arrow and its tributaries		

APPENDIX H. Specific Pollutant/Priority Substance Seasonal Data

Regulated Specific Pollutants (µg/l)											Non-Regulated Nutrients (mg/l)		
Site	**Av**	**Cd**	**Cu***	**Ni***	**Zn***	**Pb**	**Fe**	**As**	**Cr III**	**Mn***	**K**	**Na**	**Ca**
River Arrow											**River Arrow**		
ST		1	3	0	3	3	0	2	0	17	5	34	68
	☀	2	4	0	2	0	18	4	0	22	6	34	76
WTW		1	4	1	8	1	0	7	0	25	11	44	82
	☀	2	8	0	7	0	16	1	0	22	10	39	73
NFM DP		1	5	1	10	3	0	8	0	19	10	41	79
	☀	2	4	0	8	0	18	5	0	24	12	46	91
CC		1	12	0	6	2	0	4	0	16	6	26	59
	☀	2	7	0	5	0	14	1	0	13	8	33	75
KC		1	4	1	7	2	0	7	0	19	8	36	78
	☀	2	4	0	4	2	11	5	0	12	8	33	67
Main Drainage Channel											**Main Drainage Channel**		
ED		1	5	7	11	0	5	1	1	13	4	8	22
	☀	2	5	4	3	0	26	1	0	97	3	8	29
CD		1	3	1	2	1	0	3	0	12	2	8	34
	☀	2	3	0	1	0	12	1	0	20	3	8	35
WD		1	3	0	1	1	0	2	0	7	2	6	28
	☀	2	3	0	0	0	10	6	0	9	3	8	38
Ponds											**Ponds**		
P1		1	5	0	1	0	52	1	0	33	3	3	14
	☀	2	4	0	0	0	67	1	0	54	2	3	13
P2		1	6	0	0	0	12	0	0	51	3	4	20
	☀	2	10	0	0	0	78	2	0	217	3	3	19
	Spring Average												
☀	Summer Average												

Regulated Specific Pollutants (µg/l)									Non-Regulated Nutrients (mg/l)		
Site	**Cd**	**Cu***	**Ni***	**Zn***	**Pb**	**Fe**	**As**	**Cr III**	**Mn***	**K**	**Na**	**Ca**
River Arrow									**River Arrow**		
ST	-	-	-	0.006	-	<0.001	0.017	-	-	-	-	-
WTW	-	<0.001	<0.001	-	<0.001	<0.001	0.029	-	-	-	-	-
NFM DP	-	-	<0.001	-	0.002	<0.001	-	-	-	-	-	-
CC	-	0.001	<0.001	0.031	<0.001	<0.001	0.020	-	-	-	-	-
FD	-	-	<0.001	0.046	0.019	<0.001	-	-	-	-	-	-
KC	-	0.002	<0.001	<0.001	-	-	-	-	-	-	-	0.002
Drainage Channel									**Drainage Channel**		
ED	-	-	-	0.034	<0.001	-	0.012	<0.001	<0.001	-	-	-
CD	-	-	<0.001	0.006	<0.001	<0.001	0.015	-	-	-	0.002	-
WD	-	0.008	-	0.002	<0.001	<0.001	-	-	0.025	-	-	-
Ponds									**Ponds**		
P1	-	-	<0.001	-	<0.001	-	-	-	-	0.005	-	-
P2	-	<0.001	<0.001	-	<0.001	-	<0.001	-	-	0.003	-	-